University of Salford
A Greater Manchester University

# HUMAN RESPONSE TO VIBRATION IN RESIDENTIAL ENVIRONMENTS (NANR209)

*NANR209: TECHNICAL REPORT 1*

*MEASUREMENT OF VIBRATION EXPOSURE*

*31 MARCH 2011*

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# Foreword

This research was commissioned by the previous government.

The work was funded by the Department for Environment Food and Rural Affairs.

The views and analysis expressed in this report are those of the authors and do not necessarily reflect those of the Department for Environment Food and Rural Affairs.

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# Preface

This document is one component of the Defra project NANR209 ‘Human response to vibration in residential environments’ final report.

The NANR209 Final Report consists of the following documents:

- Executive summary
- Final project report
- Technical report 1: Measurement of vibration exposure
- Technical report 2: Measurement of response
- Technical report 3: Calculation of vibration exposure
- Technical report 4: Measurement and calculation of noise exposure
- Technical report 5: Analysis of the social survey findings
- Technical report 6: Determination of exposure-response relationships

The project was performed at the University of Salford between January 2008 and March 2011. During that time the following University of Salford researchers worked on the project. David Waddington, Andy Moorhouse, Mags Adams, Geoff Kerry, Rodolfo Venegas, Andy Elliott, Victoria Henshaw, Eulalia Peris, Phil Brown, Andy Steele, Jenna Condie, Gennaro Sica, James Woodcock, Deborah Atkin, Nathan Whittle, Zbigniew Koziel, George Perkins, Natalia Szczepanczyk, Sharron Henning, Ryan Woolrych, Heather Dawes, Amy Martin, Maria Beatrice Aquino-Petkos, Laura Jane Buckley, Catherine McGee, Andrew Caunce, Valentin Le Bescond, Stephanie Jones, Dawn Smail, Andrew King, Lauren Hunt, Michael Gerard Smith, Tomos Evans.

The work by the University of Salford benefited from guidance by the Defra project steering group. The Defra project steering group consisted of Richard Perkins and Colin Grimwood on behalf of Defra, Colin Stanworth representing the interests of the British Standards Institution working group for BS6472, Rupert Thornely-Taylor representing the interests of the Association of Noise Consultants, and Henk Miedema, Sabine Janssen and Henk Vos from TNO (Netherlands Organization for Applied Scientific Research).

This project benefited from guidance in the design of the vibration measurement equipment from the suppliers Guralp Ltd.

The peer review of the railway questionnaire was performed by Jim Fields, Larry Finegold, Evy Öhrström, Peter Brooker, and Gary J Raw.

This research would not have been possible without the kind cooperation of the residents that took part in the field trials.

The work presented is research performed by the University of Salford funded by Defra.

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# 1 EXECUTIVE SUMMARY

The Technical Report 1 describes the research undertaken to develop a method by which human exposure to vibration in residential environments can be assessed. That work has been carried out by the University of Salford supported by the Department of environment food and rural affairs (Defra). The overall aim of the project is to derive exposure-response relationships for human vibration in residential environments. This document in particular focuses on the equipment and methodology employed to measure vibration from different sources.

The main objective of this report is to describe the practical experience of implementing a vibration measurement protocol. Reported here are findings obtained in the field measurements and a description of a feasible method for measuring vibration for different sources. In addition, controlled tests performed to determine the suitability of the vibration mounting for various practical situations are reported.

# 2 INTRODUCTION

This technical report, describes the equipment and the methodology used for the measurement of vibration from trains, construction and internal sources in residential environments. The measurement of vibration is to be employed in a residential setting where the study of the human response due to vibration has to be determined.

The current guidance for measuring and evaluating vibration in order to assess the likelihood of adverse comment is British Standard BS 6472-1:2008 “Guide to evaluation of human exposure to vibration in buildings”. Another useful source of information regarding the measurement of vibration is the ANC “Guidelines for measurement and assessment of groundborne noise and vibration” (ANC Guidelines, 2001). Both sources of guidance agree that the evaluation of building vibration with respect to human response has to be made taking into consideration various factors relating to the vibration such as magnitude, frequency, duration and source, together with factors related to the human perception of the vibration.

The measurement approach recommended in BS 6472-1:2008 is to record acceleration time histories as close to the point of entry as possible, in effect this means taking measurements inside residences. Internal measurements should be taken in each residence studied because vibration level variation occurs from house to house related to foundations (rigidity, mass, natural frequencies, etc.), structure and number of floors as suggested by Madshus et al. (1995). However, most of the field studies investigating community response to vibration use small sets of vibration measurements and semi-empirical prediction models to determine vibration exposure.

Furthermore, in order to obtain a reliable measure of vibration exposure, it was necessary to monitor over a sufficient time period. Noise indicators are evaluated over a 24 hour period. Thus there is no basis for assuming that a shorter period is sufficient to evaluate vibration dose. In order to follow the approach of BS 6472-1:2008, 24 hour internal measurements are required for each case study. This approach is not practical considering the large number of case studies that this research involves (around 1500), so an alternative measurement protocol for each vibration source was designed and tested to ensure efficiency in time and effort.

This technical report outlines various aspects of the vibration measurement from different sources such as equipment, site selection, methodology and practicalities. It is divided into four sections. The first part provides general and specific criteria for selecting measurement sites. The second section covers the description of the measurement system; the description of the laboratory tests that have been carried out in order to determine effects of different accelerometer mounting conditions on the vibration measurements; and the measurement approach employed. The third section explains the data storage procedures. Following this, the last section presents a summary of the characteristics of each measurement site.

# 3 MEASUREMENT SITE SELECTION

The measurement site selection followed some general criteria independent on the type of vibration source. On the other hand, due to the differences between sources the selection of sites was based partially on some specific criteria for each one of the vibration sources.

## 3.1 GENERAL CRITERIA

The study measurement sites were chosen to provide representative overall socio-demographics and robust sample size, as well as to maximize both the range of exposures to vibration and the potential number of respondents. This was achieved by selecting sites within a range of distances from the source, and different kinds of properties. Mainly the sites were identified depending on the density of population and distance from the vibration source.

A number of sites were then identified at each location. Potential locations were selected on the basis of the following:

- A high concentration of residential properties in close proximity to the source with a probability that the level would be perceptible in the residences where the measurements were conducted;
- As far as possible, residences were required to be exposed only to the source of vibration of interest – there would be no interference from other sources;
- A sufficient number of respondents was required in the locality exposed to vibration exposure;
- The locations needed to be easily accessible and that would not risk compromising the health, safety and welfare of the survey and/or measurement teams.

## 3.2 CRITERIA SPECIFIC TO THE SOURCE

As well as following the above general criteria for selecting measurement sites, some specific criteria were taken into account depending on the type of vibration source under investigation.

### *3.2.1 RAILWAY*

The main criteria on which railway sites were identified were:

- The sites were required to have high railway traffic;
- Properties within a distance of 70 meters to the railway were mainly targeted to ensure a high enough vibration level perceptible for the respondents;

The search for potential locations followed the West Coast main line of the UK and resulted in sites concentrated in the North-West and the Midlands areas. Maps and aerial photographs available from Google Maps were used to identify possible sites. A shortlist of possible measurement locations was generated from desk studies, followed by a site reconnaissance to assess their suitability.

Finally, following the criteria described above, a total of twelve locations were chosen at which the surveys and the vibration measurements were to be conducted. See section 5 for tables with characteristics of the sites.

### *3.2.2 Construction Activity*

A different framework of site identification was adopted for construction vibration sources and was based on:

- The stage of the construction activity. The major part of this activity needed to take place during the spring, summer and autumn of 2010.
- It required the cooperation of the construction site management, due to the transient nature of the source.
- The vibration activity needed to comprise different types of construction sources.

Many of the identified sites were rejected as they did not meet the selection criteria or they proved to be impractical for the implementation of the measurement protocol, and the Manchester´s tram line extension was found to be the only potential measurement site.

The tram line extension in addition of meeting the selection criteria had the unique advantage of being an essentially linear process (i.e. the construction activity progresses along a “line”). Because of this feature, residences in one area of the site would have been exposed to the entire life cycle of the construction activity and can be interviewed. In the mean time, vibration can be measured further along the site and the entire lifecycle of the construction can be fully characterized. For these reasons the Manchester´s tram line extension was selected as the main focus of the construction component of this project. A shortlist of possible measurement location within the tram line project was generated from site reconnaissance to assess their suitability. See section 5 for tables with characteristics of the sites.

### *3.2.3 Internal Sources*

The site selection followed a similar framework adopted for the railway vibration component. The main criteria were to maximize the number of respondents and minimize the number of measurements (i.e. one measurement would be representative of several flats). This was achieved by selecting buildings of flats with easy access.

Potential locations were targeted in the North West of England, specifically in the Greater Manchester area. Apartment flats are generally managed by estate agent companies, and they were found to be difficult to access. Flats in which access was fairly easy were student flats in the university accommodation and sheltered accommodation (See Technical Report 5). Contact names and numbers of the guardians/managers of the buildings were used to gain access and consequently conduct interviews and measurements. See section 5 for tables with characteristics of the sites.

# 4 FIELD MEASUREMENT PROCEDURES

Due to the large volume of vibration data to be collected, there were a number of logistical and technical issues which had to be considered in the design of a practical measurement protocol. This section focuses upon the equipment and methodology employed for the measurement of internal vibration exposure.

## 4.1 MEASUREMENT SYSTEM

The measurement equipment was selected on the basis of the requirements of the project. One of these requirements was to measure levels of vibration of the order of the threshold of human perceptibility of vibration as stated in BS 6841:1987 and ISO 2631-1: 1997 (also in BS 6472:1992, superseded by BS 6472-1:2008). Another important requirement for an acquisition system was its ease of use.

The best equipment required to assess the human response to vibration in residential environments is not specified by the current guidelines. Basically, two different types of transducers can be used to measure acceleration of the order of human perceptibility: piezoelectric or force-balance accelerometers (ANC Guidelines, 2001).

From commercially available acquisition systems it was determined that Guralp CMD-5TD force-feedback strong-motion accelerometers used for seismology were the most appropriate measurement system.

The advantage of using force-feedback accelerometers is that they have a displacement transducer to measure the motion of the seismometer mass. In addition, they add an electromagnetic forcing system that has the role of minimizing the motion of the mass with respect to the seismometer case. The force necessary to keep the mass stationary is simply the gravitational acceleration. The essential feature of these systems is that the dynamic range of the instrument is dictated by the dynamic range of the electronic feedback system, and not by the dynamic range of the mechanical seismometer. This characteristic allows them to achieve large dynamic ranges (Clinton & Heaton, 2002; NMSOP, 2002).

The Guralp CMG-5TD has an in-built 24-bit digitizer; its low noise floor associated with a force-feedback transducer (˜10$\mu$ $ms^{-2}$ across the frequency range of interest), its ease of use of the system, and its ability to synchronize multiple units via GPS. Figure 1 shows a photograph of the measurement system; the dimensions of the units are 140 *mm* height and 180 *mm* diameter and have a mass of 3.8 *Kg*.

**Figure 1** Guralp CMG-5TD force-feedback strong-motion accelerometer

The most important features of the Guralp CMG-5TD accelerometers are described below.

#### 4.1.1 DYNAMIC RANGE AND FREQUENCY RESPONSE

The clip level of the Guralp CMG-5TD transducers is approximately 10 $ms^{-2}$, which far exceeds the amplitude of environmental vibration likely to be encountered in the field when measuring railway traffic or construction activity inside properties (ISO 4866:1990). This upper bound of vibration expected to be measured (10 $ms^{-2}$) plus the bound of human perceptibility of vibration in a vertical $W_b$ weighted peak acceleration as defined in BS 6472-1:2008 (0.015 $ms^{-2}$) demand a dynamic range greater than 130dB. For unattended measurements at a large number of locations as the study required precedence must however be given to avoiding overload. The Guralp CMG-5TD has an in-built 24-bit digitizer coupled with a transducer that has an extremely low noise floor, meet the requirements for measuring this upper and lower bounds cleanly; see Table 1.

| Dynamic Range | Clip Level (Output sensitivity) |
|---|---|
| >140 *dB* for 0.005-0.05 *Hz* | 1*g* |
| >127 *dB* for 3-30 *Hz* | |

**Table 1** Manufacturer´s specifications (Guralp Systems Limited, 2007)

The frequency range of interest is below 100Hz (BS 6472-1:2008). The units have a built-in low-pass filter at 100 *Hz* which starts rolling off from 80 *Hz*.

#### *4.1.2 UNIT SYNCHRONIZATION*

The internal clock used in the Guralp CMG-5TD accelerometers is set either by receiving timing signal from the GPS satellite network via an attached GPS antenna, or by taking information from an external clock. Synchronization between the units is essential as different units at different positions have to measure the same vibration activity. Due to the logical problems associated with running long cables outside of properties through the windows during internal measurements, it was not often practicable to setup the GPS antennas required to synchronize the internal clocks of the units. Moreover, it was observed that Guralp CMG-5TD internal clocks without receiving a timing signal via GPS drift over long durations and changes in ambient temperature. The manufacturer addressed this problem introducing a precision real-time external clock to the measurement set-up which consists of a microprocessor-controlled, temperature compensated quartz oscillator and real time clock counters. Once synchronized by a GPS time source, the real-time clock can maintain time keeping to an accuracy of $1.2 \times 10^{-8}$ *s* and has been shown to perform with a drift of less than 1ms over a period of 48 hours (Guralp Systems Limited, 2007). All the external clocks were synchronized by a GPS time source overnight, without the need later on to connect any GPS antenna when internal measurements are conducted.

#### *4.1.3 EASE OF USE*

Due to the large number of measurements the project required, the ease of use of the equipment in the field was a decisive factor. The setup of the Guralp CMG-5TD equipment in the field was found to be a fast and easy process. As the equipment is configured off-site prior to any fieldwork, installation of the equipment on site only requires that the operator orientates the unit to the North, ensure the unit is correctly levelled and supplies power to the unit (lead acid battery). Once power is supplied, the units were configured to begin recording time history data to its flash memory without any further interaction required from the operator.

#### *4.1.4 RELIABILITY*

The Guralp CMG-5TD equipment proved to be robust and reliable under the conditions encountered during field measurements. The sensor system is self-contained and the internal digitizer ensures the sensor is completely isolated. Moreover, the accelerometer housing itself is completely waterproof; with a hard anodised aluminium body and “O” ring seals throughout which allowed prolonged measurements under wet weather conditions.

#### *4.1.5 CALIBRATION*

The calibrated response of the sensor is measured at the factory, the results of which are provided with the Guralp Units in the form of a calibration certificate (See Appendix 3). However, the sensor response can be checked using the manufacturers interface by injecting a known calibration signal into the sensor in use which gives rise to an equivalent acceleration (See Figure 2) that is added to the measured acceleration to provide the sensor output. The signal injected into the sensor can then be compared with the sensor output to determine if the sensitivity of the sensor is consistent with the values provided by Guralp. This procedure was performed off-site before starting each set of field measurements to ensure the accelerometers were properly functioning.

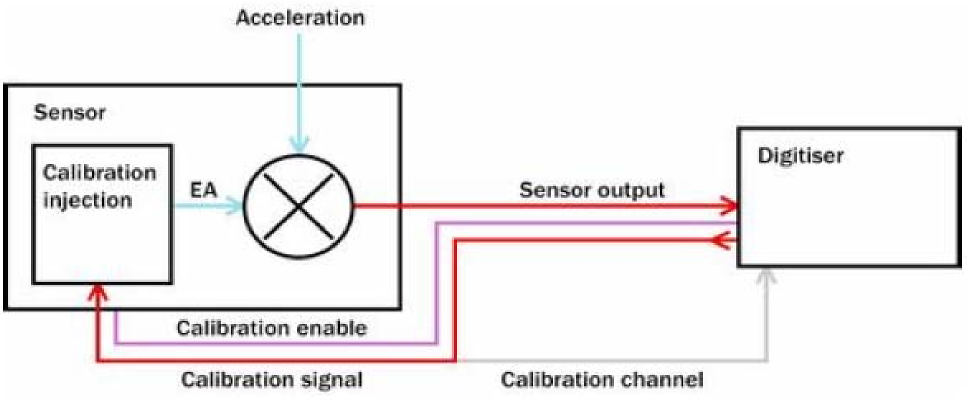


**Figure 2** Schematic of Guralp CMG-5TD calibration check taken from (www.guralp.com)

Figure 3 shows the evolution of the calibration error factor over time. The error is the difference between the injected reference acceleration and the measured acceleration. The test was performed on one instrument. The graph suggests an average behavior of the instrument of less than 3% of error. The two spikes at around 5% are thought to be mainly due the background level. The performance of all instruments resulted in errors between 3%-3.5%. This uncertainty related to the instrument is considered negligible in the evaluation of the human exposure reported in technical report 3.

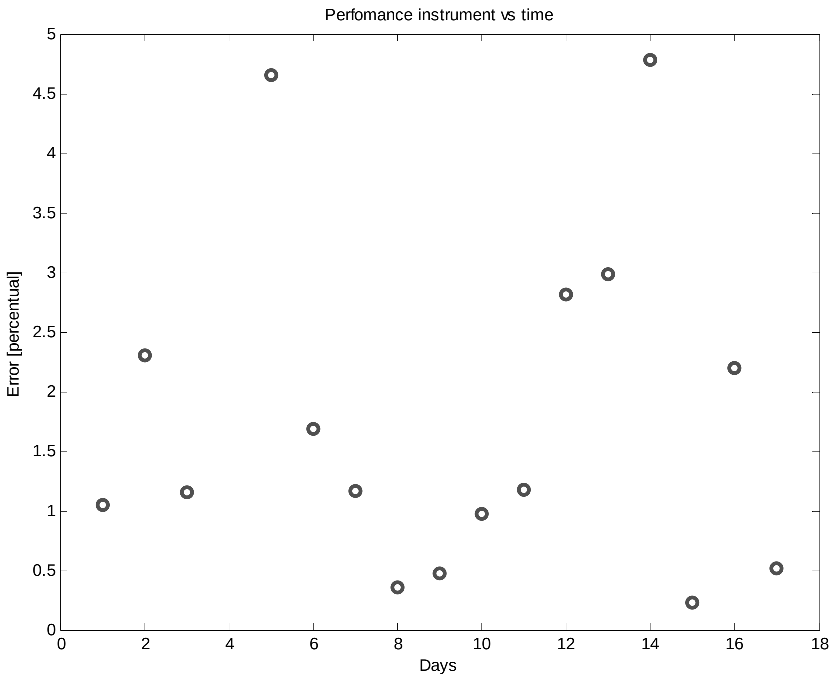


**Figure 3** Calibration error of Guralp CMG-5TD over time.

## 4.2 TRANSDUCER MOUNTING

The motion of the surface being measured has to be faithfully reflected by the transducers. The current methods of mounting an accelerometer onto the structure of interest are described in BS ISO 5348:1998. Due to the characteristics of Guralp CMG-5TD (its mass, dimensions, design, etc.) most of the techniques described in BS ISO 5348:1998 are impracticable. Moreover, as the requirements of this project involved measurements inside occupied residences and were evaluated considering that a range of different surfaces can be encountered, some of the methods to be employed must not damage or leave permanent marks in any surface.

Ideally, measurements of vibration in a respondent's property were conducted by mounting the Guralp CMG-5TD accelerometers in the centre of the room in which the respondent stated they can feel the highest magnitude of vibration (ANC guidelines, 2008). However, due to the mass of Guralp CMG-5TD instruments (3.8 *Kg*), any mounting resonances which may occur in the frequency range of interest due to mounting the instrument on different surfaces had to be considered. For this reason, some laboratory tests were conducted to determine the effect of mounting the transducers on different surfaces along with an investigation into any action that could be taken to reduce these effects (Woodcock et al., 2009).

### *4.2.1 MOUNTING CONDITIONS*

One of the most commonly encountered variables when mounting the transducers in dwellings is whether the units are mounted on a rigid floor (i.e. a timber or concrete floor) or a floor with a compliant covering (i.e. carpet). A simple laboratory test was conducted to determine the effect of mounting the Guralp CMG-5TD accelerometers on different types of carpet and on rigid surfaces. Full details of the setup and results for this investigation are explained and illustrated in Appendix 1.

The material under investigation was laid on a concrete slab and a Guralp CMG-5TD accelerometer was mounted on it either directly, on a ceramic tile (4 *mm* x 300 *mm* x 300 *mm*), or on a circular metal plate (5 *mm* thick x 210 *mm* diameter). Two B&K type 4379 accelerometers were glue mounted directly onto the slab orientated in the direction of interest (tests were conducted for the vertical and in plane components) as a reference measurement. The slab was excited by striking it ten times with a sledgehammer in the vertical and horizontal directions.

In general it was found that by using a steel plate (provided by the manufacturer) the effect of mounting the Guralp CMG-5TD accelerometers on carpet was greatly reduced. However, when mounting the Guralp CMG-5TD on a rigid floor using the tile or plate an increase in response was observed. Figure 4 and Figure 5 show the results of the control test and a test on 1 *cm* thick carpet in the vertical direction. The cause of the discrepancy at low frequencies (< 10 *Hz*) is thought to be an artefact of the measurement setup (e.g. mounting of B&K accelerometers, excitation of concrete slab, post processing, etc.) and not the true response of the Guralp CMG-5TD accelerometers whilst the drop off in response above 80 *Hz* is due to the 100 *Hz* low pass filter built into the Guralp CMG-5TD accelerometers.

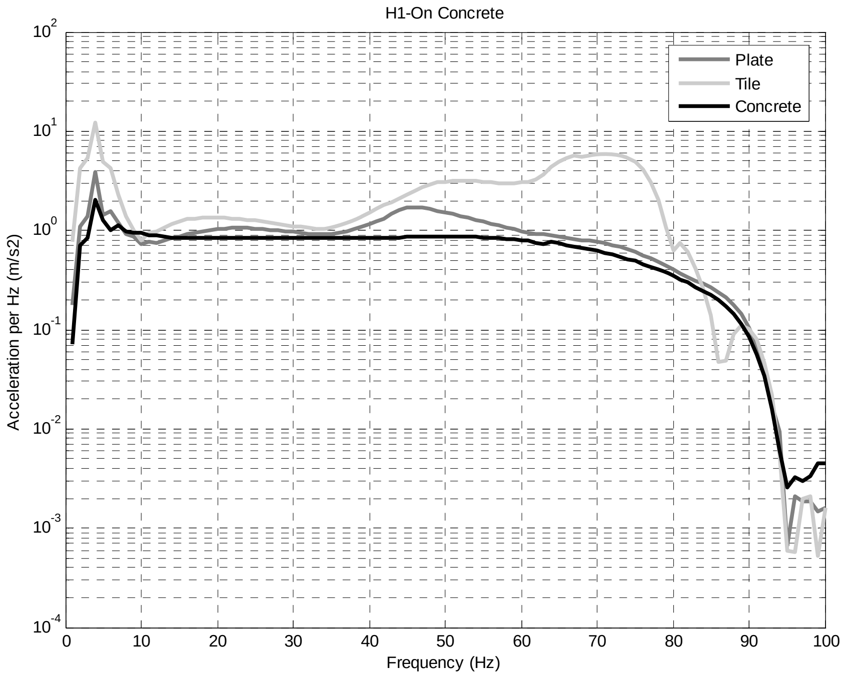


**Figure 4** Results of mounting conditions tests on a concrete slab for three cases (Guralp CMG-5TD mounted directly on concrete, on a tile on concrete and on a plate on concrete.

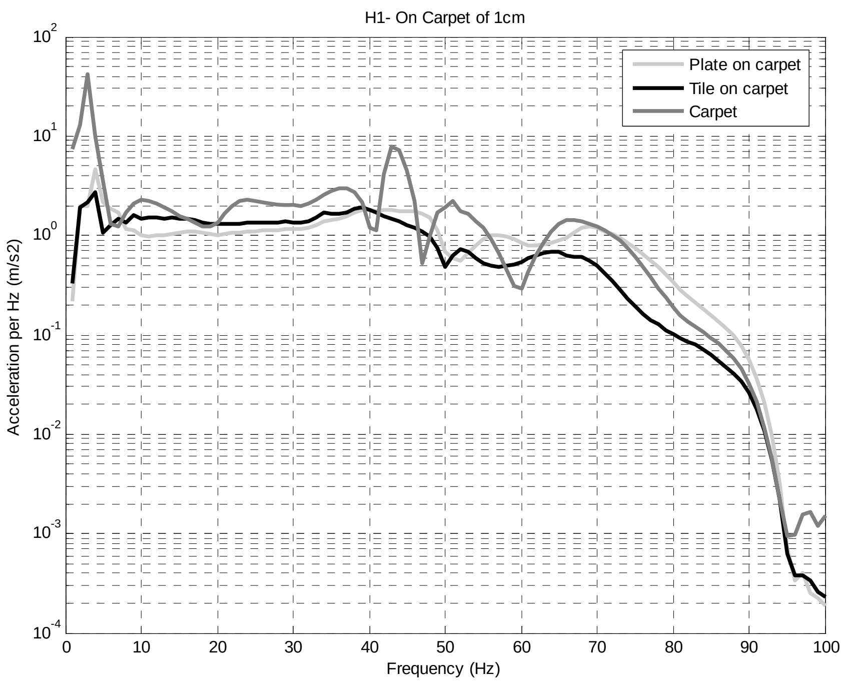


**Figure 5** Results of mounting conditions tests on a 1cm thick carpet for three cases (Guralp CMG-5TD mounted directly on the carpet, on a tile on carpet and on a plate on carpet.

Based on the results of these tests the following guidance was adopted when mounting the Guralp CMG-5TD accelerometers:

- On rigid surfaces such as concrete and timber floors, the accelerometers were mounted directly on the surface;
- On compliant surfaces such as carpets and linoleum, the accelerometers were mounted on a metal plate.

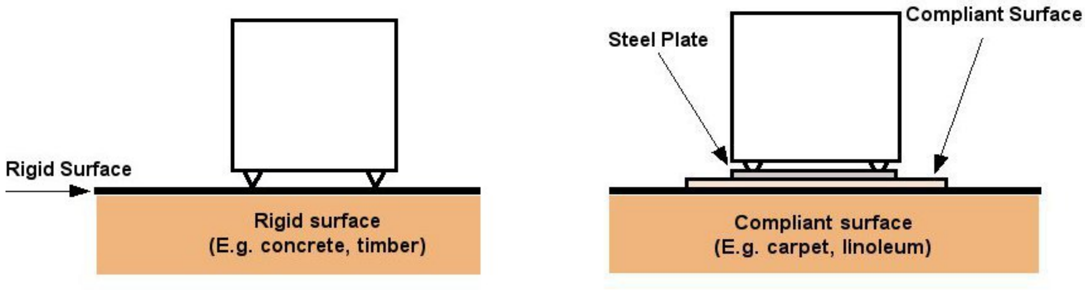


**Figure 6** Scheme of mounting best practice

### *4.2.2 EFFECT OF HUMAN LOAD ON A BEAM*

Work has been done to determine the effect of a human load on the measured vibration of timber floors in buildings.

It is recommended in the British Standard BS 6472-1:2008 to measure vibration as close to the body point of entry as possible. In some cases, the individual perceives vibration when standing on a beam. In practice, vibration is measured on an unloaded beam. Thus, the influence of the standing human body on the measured vibration in terms of frequency and magnitude was explored. This has been approached in a similar way as the vibration transmission of machinery. In this way, the ratio between the loaded and the unloaded velocity can be expressed for every point of the structure as a function of the mobility of the human body and the structure. Calculations and results are detailed in Appendix 2.

The influence of a standing human body on a beam is determined using the relation that links the ratio between the velocity of the loaded ($\upsilon_B$) and unloaded ($\upsilon_{fs}$) floor with the mobility of a beam with a damping $\eta$ =0.37, and the human body as seen in Figure 7 (for body weights of 60, 70, 80 and 90 *Kg*.)

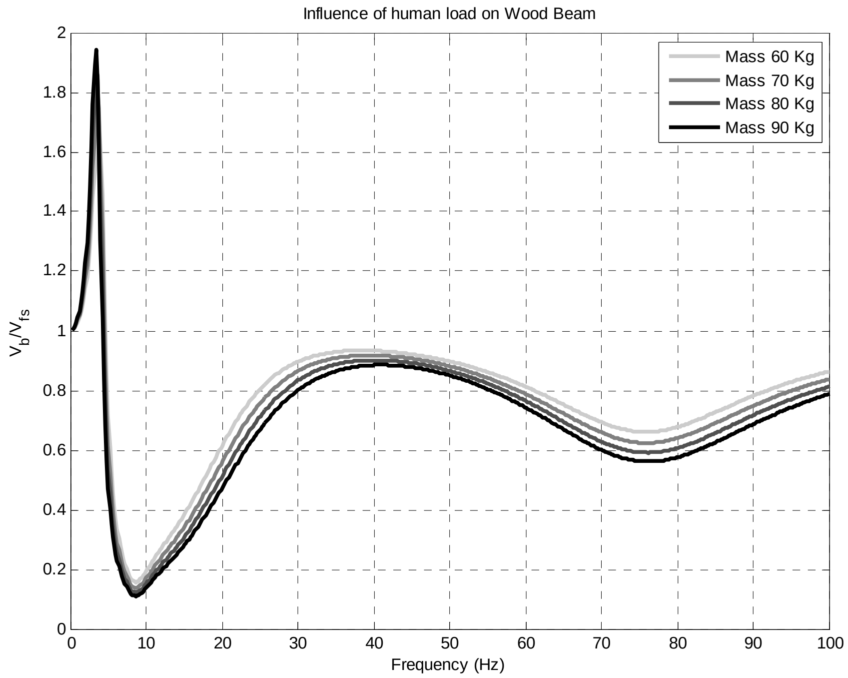


**Figure 7** Influence of the human load on a wooden beam.

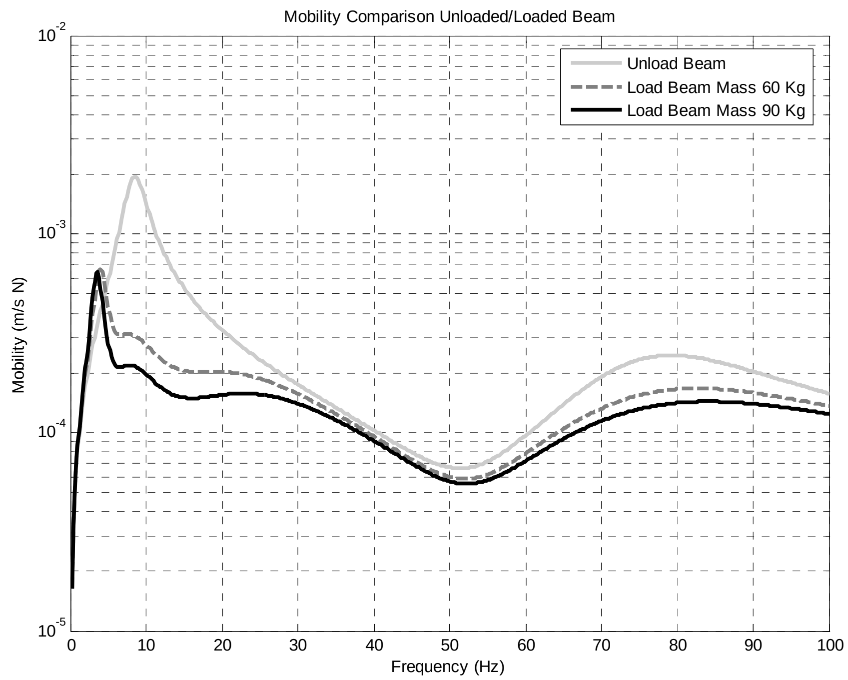


**Figure 8** Comparison between loaded and unloaded beam

The results show that when vibration is measured on an unloaded beam of a timber floor, a small overestimation (see Figure 8) of the vibration transmitted to the human body (i.e. when the beam is subject to a human load) is expected. Note that the wooden floor damping ratio is an approximation and was derived from Craik's (1996) empirical relationship. The first resonance peak of the beam is at around 8 Hz. In order to estimate more accurately the influence of a human load a real estimate of the damping is required. Further investigations taking into account real damping values of typical floors are needed.

## 4.3 Measurement Approach

Different approaches are required to assess vibration from different sources in residential environments. The most important factors which dictate how the vibration from a specific source will be measured are the characteristics of vibration (frequency, amplitude, direction, continuity/intermittency). Other factors considered in the design of the methodology were duration and time of the day where the vibration occurs and the proximity of the source. In this section a detailed approach is described for each one of the vibration sources.

### *4.3.1 Railway*

Based on practical experience gained in the field, the interaction between the social survey and vibration measurement teams onsite was conducted as follows:

- The social survey team arrive on site ahead of the vibration team and conduct as many interviews as possible (See technical report 2);
- Following an interview, the respondent is asked if they are willing to allow a vibration measurement within the property at a later date and the telephone number of the respondent is taken;
- The vibration team call to book appointments for internal measurements prior to arrival on site;

This approach has yielded a success rate of 63% internal measurements from interviews with an internal agreement.

Railway as a source of vibration was found to be permanent, continuous and predictable (i.e. at any arbitrary time window it is almost certain that vibration from the source will be present). Considering the nature of railway vibration, it was possible to carry out detailed internal measurements in any property in which the resident allowed measurements to be conducted. Due to the continuous nature of railway vibration at the site chosen, sufficient data could be acquired from an internal measurement in around thirty minutes.

The measurement set-up was based on long-term monitoring measurements and synchronized short-term internal measurements, in order to calculate control-to-internal velocity ratios. The concept is illustrated in Figure 9.

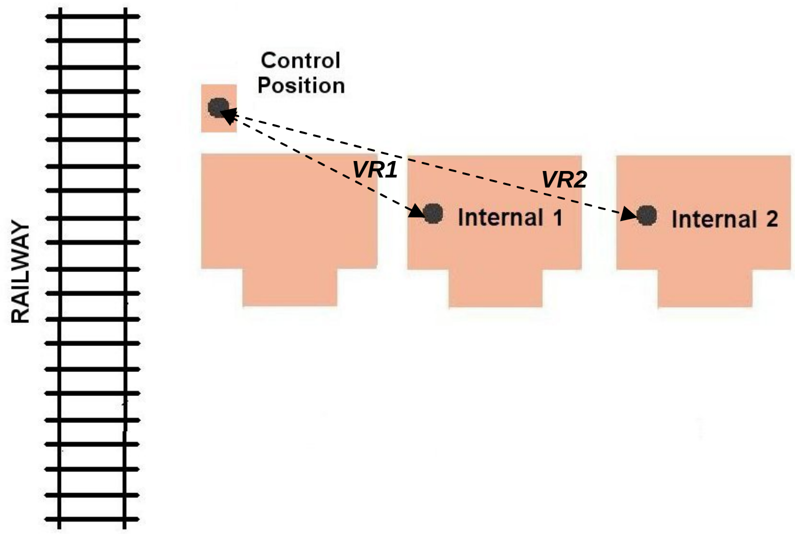


**Figure 9** Overview of measurement set up for railway traffic

Control position measurements: It is a 24-hour long term monitoring position representative of the site (providing a representative sample of railway traffic). It is first placed at the arrival on site. It is selected in a secure location in the near field as the majority of residences of interest were conducted in the near field of the railway. In practice, the control position was generally setup in a resident's garage or garden shed, to avoid contamination from other internal sources.

Internal Measurements: There are short term measurements, which are taken for between 20-30 minutes in order to capture a limited number of train passes. After the control position is allocated, internal measurements are conducted in properties which agreed for an internal measurement after taking part in the survey. Ideally, internal measurements are taken by mounting the Guralp CMG-5TD units in the room in which the respondent states they can feel the highest magnitude of vibration and following the set-up described in section 3.2.1 (mounting conditions).

### *4.3.2 Construction Activity*

The major practical challenge associated with the measurement of environmental vibration from construction activity was the transient nature of the source. It was identified early in the site reconnaissance process that the times of operation of the source were hugely variable. Mitigation of this was sought via liaison with the site manager to attempt to build a rough timetable of operation; however, this was sometimes found to vary.

Another major consideration in the development of the protocol was the dynamic nature of sites identified. As mentioned is section 2.2.2 (Site identification) the construction activity on the sites identified for conducting the research progresses in a nominally linear fashion from West to East. This leads to the situation whereby potential respondents to the East of the site have not been exposed to the major part of the activity and therefore cannot be surveyed; conversely, potential respondents to the West of the site have been exposed to vibration but the major part of the activity has passed and therefore cannot be measured. Based on consultation with the main contractor of the site, it has been assumed that once the major part of the activity has passed, each area of the site will have been subject to nominally the same activity at some point over the lifespan of the construction project.

Considering the unpredictable hours of operation and the dynamic nature of the source the following approach was proposed:

- The social survey team commences surveying at areas of the site at which the major part of the construction activity has recently concluded; in this way all respondents will have experienced the same nominal vibration exposure (See technical report 2).

- Detailed vibration measurements are timed so as to start at an area of the site at which the major part of the construction is yet to commence.

The measurement approach for construction is illustrated in Figure 10 and involved the following:

- Long term monitoring of the entire lifecycle of the construction at that area;

- Well controlled external measurements at different distances from the source using array techniques to determine site characteristics (e.g. attenuation laws) and control-to-external velocity ratios;

- Internal measurements in representative properties to determine external to internal velocity ratios.

Therefore, compared with the measurement protocol implemented for rail, the approach for construction required more emphasis on extrapolation and correction of the measured levels from one site to estimate exposure in other sites.

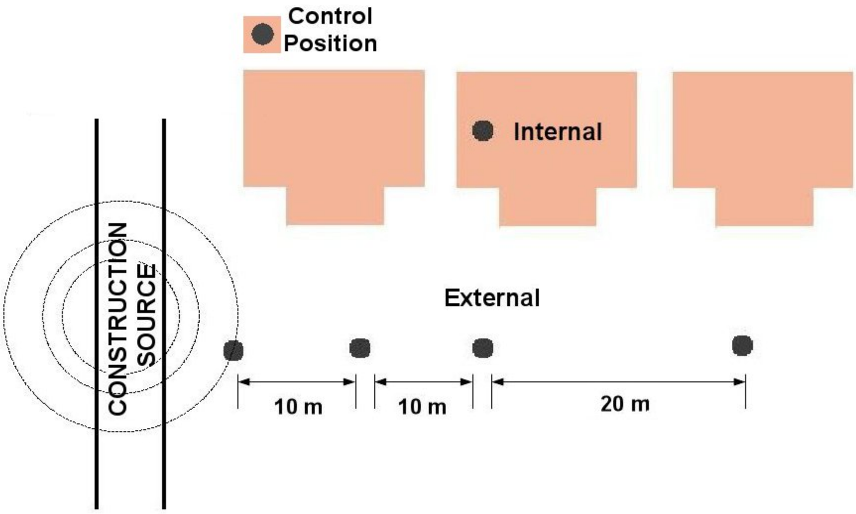


**Figure 10** Overview of measurement set up for construction activity

Control position measurements: It is long a term monitoring position representative of the site (between four and eight weeks proved to be enough time for having a representative sample of the construction activity). It is first placed at the arrival on site. It is selected to be in a secure location in the near field of the source as the majority of residences of interest are in the near field of the activity. In practice, the control position is generally setup in a resident's garage avoiding in this way contamination from other internal sources.

Internal Measurements: They are short term measurements eventually taken inside random properties (i.e. these properties might have not taken part of the survey) close to the construction vibration source in periods in which high magnitude vibration events occur.

External Measurements: External measurements are taken in periods in which high magnitude vibration events such as piling occur. These short measurements are taken on the pavement normal to the source in the form of a linear array extended to 50 *m* from the source.

### *4.3.3 INTERNAL SOURCES*

Internal sources of vibration such as washing machines, door slams, foot falls etc. are not continuous and predictable (i.e. it is not known when the vibration will be present). Other difficulties associated with measuring internal sources were the unknown location of these sources, the unknown magnitude of vibration and the contamination from other sources. Moreover, it is more likely that internal sources of vibration are encountered in flats, where appliances and foot falls can be noticed by surrounding neighbours. Ideally, long-term internal measurements should be conducted at the flat of each respondent. This is practically difficult to achieve due to the large number of accelerometers required and thus only few long term monitoring instruments are placed in strategic positions.

The interaction between the social survey and vibration measurement teams onsite was conducted as follows:

- Having gained access to the building flats (i.e. asking permission to the guardian or officer responsible) the social survey team arrive on site ahead of the vibration team and conduct as many interviews as possible (See technical report 2);
- The vibration team call the person responsible of the building to gain access and arrange the measurement locations which ideally are empty flats or spare guest rooms;

The measurement approach was based on long-term monitoring measurements in strategic points of the building in order to estimate vibration levels in all properties where a questionnaire was completed. The concept is illustrated in Figure 11.

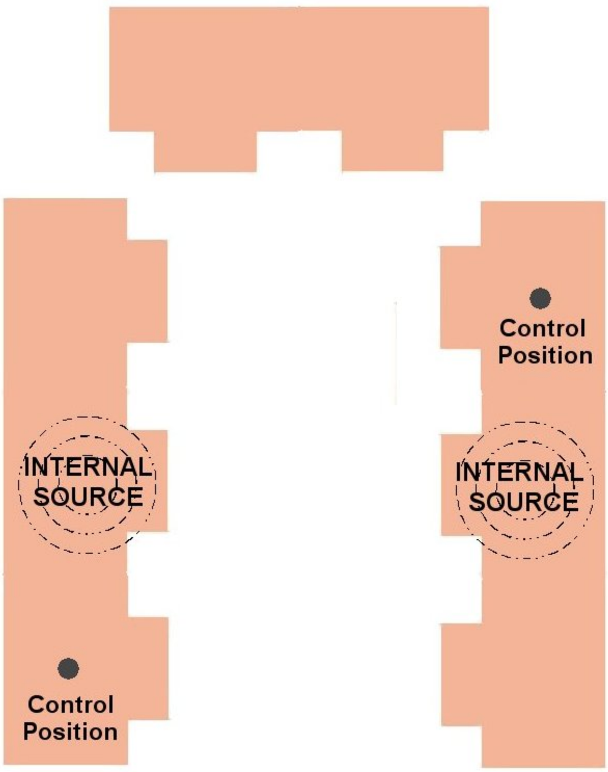


**Figure 11** Overview of measurement set up for internal sources

<u>Control position measurements</u>: It is a 24-hours long term internal monitoring position and it is placed when possible in an empty room or a secure location at each level floor of the building;

# 5 DATA STORAGE PROCEDURES

Due to the large volume of vibration data collected on site, it was vital to organize the data stored in the system so each measurement was unique and could be easily identified. This section focuses upon how the vibration data is stored on the system and how it is labeled and organized after it has been transferred to the database.

## 5.1 INITIAL STORAGE

During the field measurements, vibration data is recorded and stored in the internal memory of the Guralp CMG-5TD units (4*GB* of internal flash memory is available). The internal memory allows for long-term measurements to be made without the need for an external acquisition system. It is estimated that a tri-axial 24-hours measurement sampled at 250 *Hz* will generate approximately 520 *MB* of data.

Following the competition of measurements at a site, all recorded data is downloaded from the internal memory of the Guralp CMG-5TD units to a SCSI disk and subsequently transferred to a PC for analysis. The three components of the control and internal or external measurements for each case study are archived into single .gcf (Guralp compressed format) files via Scream! (Guralp PC interface). This is then labeled with a unique identifier which links the file with the relevant social survey questionnaire.

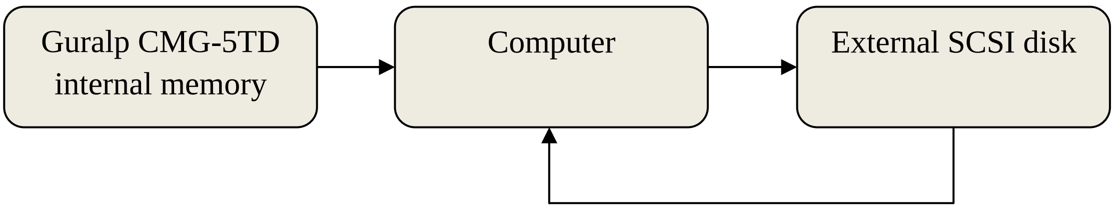


**Figure 12** Initial Storage: data from internal memory is controlled by the computer and transferred to an SCSI disk. Data stored in the SCSI disk can be accessed from the computer.

## 5.2 LABELLING

Figure 13 shows an example of the data for one case study, the top three traces are the three components of the corresponding control position measurement. When the time history vibration data is cut into measurements each of the measurements is labelled with a unique code that relates the vibration measurement with the relevant questionnaire. The storage protocol concept is shown on Figure 13.

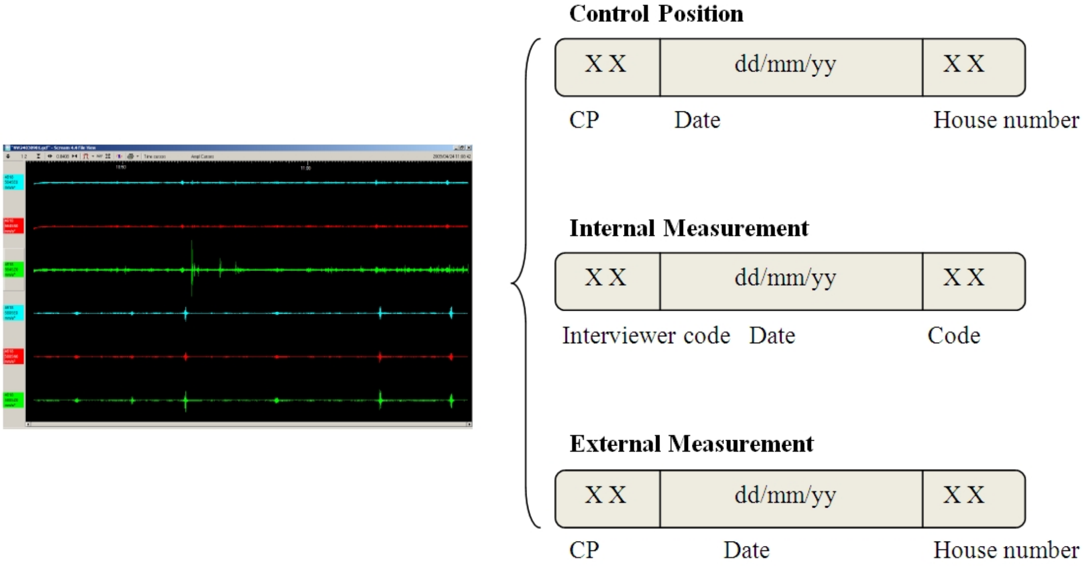


**Figure 13** Data labelling procedure

# 6 Summary of Measurement Sites

Section 2 described the selection criteria used to identify potential sites for conducting vibration measurements. Relevant information of each site has been summarized for railway, construction and internal measurements.

## 6.1 Railway

Interviews and measurements were conducted at a total of twelve sites. In total, measurements of railway vibration have been conducted internally in 522 properties, which is 56% of the total number of interviews. However, many respondents didn´t agree to the use of vibration monitoring equipment at their property so in that case considering that internal agreements were not achieved for all respondents, the percentage is slightly higher, achieving a total of 63% of internal measurements over internal agreements.

## 6.2 Construction Activity

Interviews and measurements were conducted at two different sites. Each site had a particular type of construction activity. In Site A an adaptation of an old railway line for the new tram line infrastructure was conducted. In site B a busy road was reconstructed to take in the new tram line.

## 6.3 Internal Sources

Measurements and interviews were conducted at two different kind of flats (Student accommodation A and sheltered accommodation B). Control positions were located in empty rooms and corridors.

| Site | Total interviews | Total internal measurements | Total control positions | % Measurements over interviews | % Measurements over internal agreements | Characteristics of the site |
|---|---|---|---|---|---|---|
| A | 119 | 69 | 17 | 58% | 62% | High speed line |
| B | 29 | 9 | 3 | 31% | 35% | High speed line |
| C | 9 | 6 | 3 | 67% | 86% | High speed line and freight line |
| D | 72 | 47 | 14 | 65% | 72% | High speed line and freight line |
| E | 65 | 37 | 13 | 57% | 64% | High speed and freight line |
| F | 26 | 13 | 7 | 50% | 59% | Underground railway |
| G | 112 | 69 | 12 | 62% | 64% | High speed line and freight line |
| H | 159 | 85 | 16 | 53% | 80% | High speed line, busy roads and airport nearby |
| I | 164 | 90 | 31 | 55% | 62% | Low speed line, close to station. |
| J | 78 | 48 | 13 | 61% | 70% | High speed and freight line |
| K | 51 | 22 | 8 | 43% | 52% | High speed and freight lines |
| L | 47 | 27 | 12 | 57% | 66% | High speed and freight line |
| **TOTAL** | **931** | **522** | **149** | **56%** | **63%** | |

**Table 2.** Summary of railway measurement sites

| Site | Total interviews | Total internal measurements | Total control positions | External measurements | Characteristics of the site |
|---|---|---|---|---|---|
| A | 161 | 1 | 1*30 days | At distances from 10 *m* to 60 *m* | Existing railway, remodelling for tram. Activities measured: excavation, piling, drainage and track works |
| B | 189 | 4 | 1*30 days | At distances from 5 *m* to 50 *m* | Tram line being built on the road. Activities measured: excavation, compaction, drainage and track works |
| **TOTAL** | **350** | **5** | **2** | **From 5 to 60 *m*** | |

**Table 3** Summary of construction activity measurement sites

| Site | Total interviews | Total control positions | Characteristics of the site |
|---|---|---|---|
| A | 99 | 5*24 hour | Easy access. Student flats. Three level buildings. |
| B | 51 | 2*24 hour | Easy access flats. Two level buildings. |
| **TOTAL** | **150** | **7** | |

**Table 4** Summary of construction activity measurement sites

# 7 DISCUSSION

The main objective of the field measurements was to record vibration as close to the point of entry of the respondent as possible.

Characteristics of commercially available vibration monitoring equipment were investigated and after a field trial the Guralp CMG-5TD units proved to be fully capable for undertaking the requirements of this project. It is believed that this equipment is the best currently available for measuring accurately the magnitude of vibration within the frequencies of interest. A singular feature is the ability to perform sample level synchronized measurements between remote units. The key features of the Guralp CMG-5TD equipment are its portability, high dynamic range, speed of setting up and easy data storage.

A measurement methodology was developed to reliably acquire the vibration data required. A protocol was designed to measure railway vibration based on a long term monitoring position and short term synchronized measurements order to calculate control-to-internal velocity ratios. This approach proved to be impractical for measuring construction vibration due to the transient nature of the source. Thus, measurements of construction activity were based on external array measurements. Internal source measurements were based on long-term monitoring positions inside residences. This fact suggests that different measurement approaches to measure vibration are needed depending on the nature of the vibration source.

Laboratory tests pointed out the differences in frequency response when mounting the units on rigid and carpeted floors. The results suggested that different mounting approaches have to be used depending on the surface encountered. A flat frequency response is achieved when Guralp CMG-5TD is mounted on a rigid floor and amplifications are observed when it is mounted on carpeted floors. It was found out that to avoid resonances when mounting the instrument on a carpeted floor, the Guralp CMG-5TD has to be mounted on a metal plate.

The theoretical simulations on the influence of the human load on a beam showed small differences on the measured vibration between loaded and unloaded beams. However, in order to estimate accurately the influence of a human load, a reliable estimate of the damping is required. Further investigations taking into account real damping values of typical floors are needed.

# 8 CONCLUSIONS

This technical report has aimed to give detailed information of the field measurement approach employed for each vibration source, the characteristics of the measurement system and the laboratory tests conducted in order to explore the best practice for mounting the accelerometers.

The vibration measurement equipment (strong-motion force-feedback accelerometer) has been proven to be suitable for the task and allowed high-quality vibration data to be obtained both externally and internally. Low level vibration events in residences can be reliably measured. The compact design and short setup time of the Guralp CMG-5TD system means minimal disruption to residents.

Informed by laboratory tests, guidance has been developed for mounting the accelerometers on different surfaces likely to be encountered in the field. The results showed that mounting the Guralp CMG-5TD directly on carpet can result in some amplification at certain frequencies and so a metal plate attached to the legs of the instrument has to be used when measuring vibration on carpeted surfaces.

Different measurement approaches have been designed for each of the vibration sources. These individual approaches optimized the logistics of the interaction between vibration and social survey team and yielded a 56% of internal measurements taken inside properties (case of railway study).

The measurement concept for measuring railway vibration consisted of long term vibration monitoring at an external position (garage or shed) along with time synchronized short-term internal snapshot measurements. This approach was found to be impracticable for measuring construction activity vibration due to the unpredictable hours of operation and the dynamic nature of the source. Thus, the approach for construction required more emphasis on extrapolation and correction of measured levels from one site to estimate exposure in other sites. Flats were selected to measure internal sources of vibration and the concept was based on long term monitoring instruments placed in strategic positions of the buildings.

In total 931 interviews and 522 internal measurements of railway vibration were collected at 12 sites concentrated in the North-West and the Midlands areas of UK. 350 interviews of construction activity were collected at two sites located in the Greater Manchester area. 150 interviews were collected for internal sources.

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# APPENDIX 1: MOUNTING CONDITION TESTS

A simple laboratory study was conducted to determine the effect of mounting the Guralp CMG-5TD accelerometers on different types of carpet and any action that could be taken to reduce these effects. The setup for these measurements is illustrated in Figure 15 and Figure 16; the material under investigation was laid on a concrete slab and the Guralp CMG-5TD accelerometer mounted upon it either directly, on a ceramic tile, or on a circular metal plate. Two B&K type 4379 accelerometers were mounted directly onto the slab orientated in the direction of interest (tests were conducted for the vertical and in plane components). The slab was excited by striking it ten times with a sledgehammer in the vertical and horizontal directions (See Figure 15). The experiment was conducted for 15 *mm*, 10 *mm*, and 7 *mm* thick carpets as well as a control measurement, which was taken with the Guralp CMG-5TD unit mounted directly onto the concrete slab. The data from the tests were analyzed by linearly averaging the magnitude Fourier spectra of ten impacts and calculating the velocity ratio between the two systems ($H_1$).

$$H_1(f) = \frac{B(f)}{A(f)} \cdot \frac{A*(f)}{A*(f)} \qquad \textbf{Equation 1}$$

Where $A(f)$ and $B(f)$ are the Fourier spectra of the B&K and Guralp CMG-5TD respectively.

The findings of these tests are summarized in Table 5. From these observations, the following guidance for internal mounting methods was incorporated into the measurement protocol:

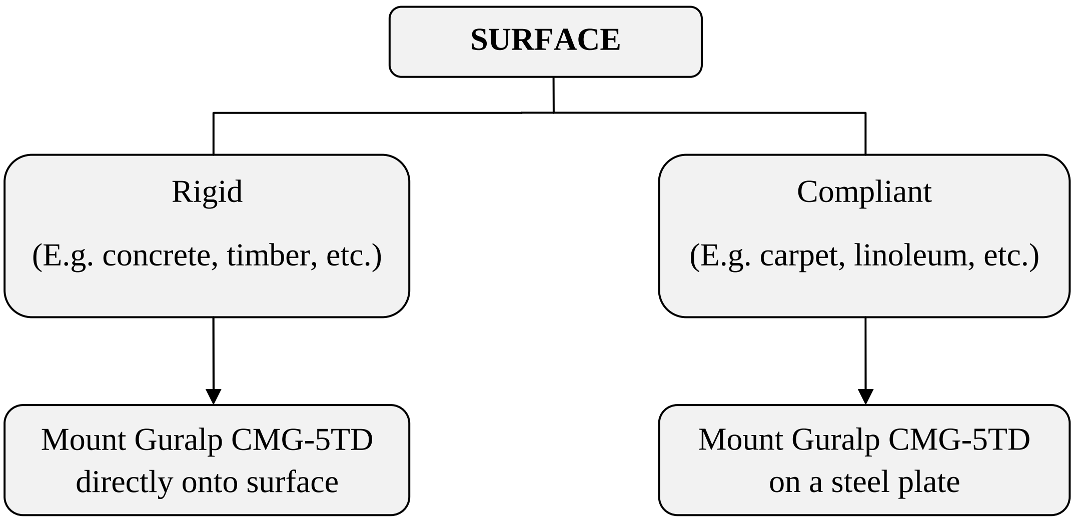



**Figure 14** Guidance for internal mounting method

| SURFACE | MOUNTING | OBSERVATIONS |
|---|---|---|
| CONCRETE | Guralp CMG-5TD Feet | Vertical: Error of 1 *dB* from 5 *Hz* to 60 *Hz* |
| | | Horizontal: Error of 3 *dB* from 10 *Hz* to 30 *Hz* |
| | Tile | Vertical: Certain amplification from 35 *Hz* |
| | | Horizontal: Variation in response from 35 *Hz* |
| | Plate | Vertical: Similar to Guralp CMG-5TD feet response but with an amplification at 45 *Hz*. |
| | | Horizontal: Very similar to Guralp CMG-5TD feet |
| CARPET | Guralp CMG-Feet | Vertical: Around 5 *dB* error at frequencies from 0 to 30 *Hz*. Complex frequency-dependent behaviour for thick carpet. Significant variation in response for thinner carpets. |
| | | Horizontal: Error of more than 3 *dB* from 10 *Hz* to 25 *Hz*. Error between 5 *dB* and 10 *dB* at 30 *Hz* depending on carpet thickness. High variation across frequency range. |
| | Tile | Vertical: Increased response of 2 *dB* error from 8 to 30 *Hz* for a 1 *cm* thick carpet (Boarder range for thicker carpets and narrower range for thinner carpets). |
| | | Horizontal: Error of around 2 *dB* from 10 to 30 *Hz*. Apparent reduced response above about 70 *Hz* (possibly due to slipping) |
| | Plate | Very similar to tile |

**Table 5** Summary of findings of mounting condition experiments

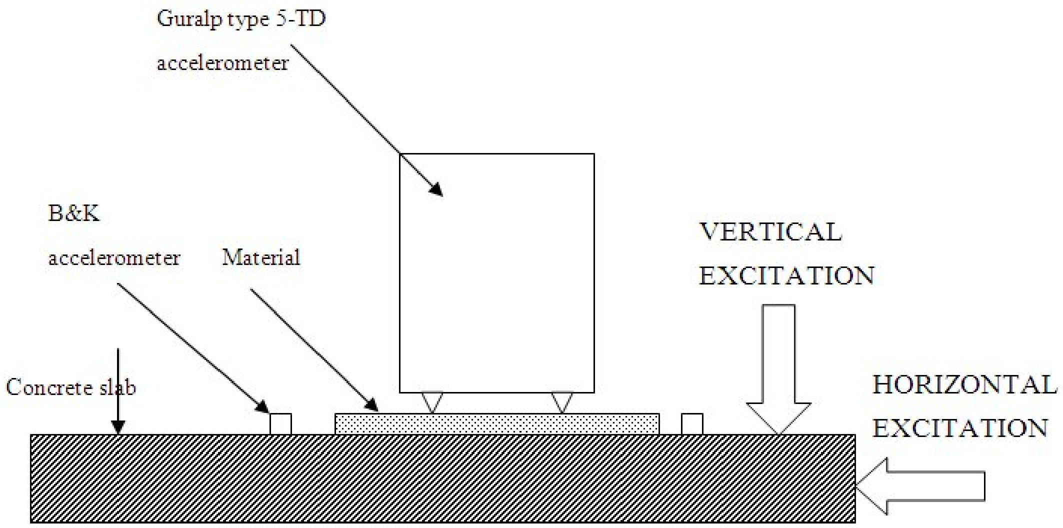



**Figure 15** Section view of setup for laboratory measurements of mounting conditions

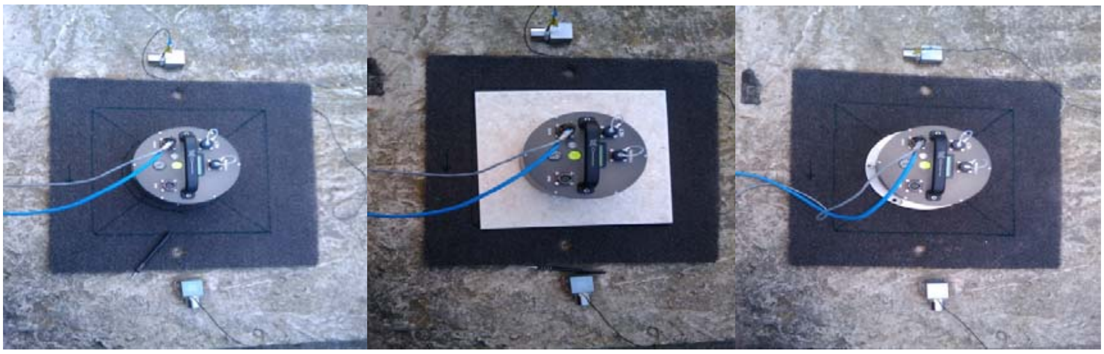


**Figure 16** (From left to right) Guralp CMG-5TD unit mounted directly on carpet, on carpet on a ceramic tile, and on carpet with a metal plate.

Below are presented figures for each case study. The figures represent velocity ratios between B&K accelerometers and Guralp CMG-5TD. Each velocity ratio is presented for each mounting condition (Concrete, carpet 1.5 *cm*, 1 *cm*, 0.7 *cm* thick) and for vertical and horizontal directions. The velocity ratios for vertical direction show discrepancies at around 4 *Hz*, this is thought to be due to the measurement set up. The explanation of these discrepancies at around 4 *Hz* can be found in Figure 17 which suggests that there was little energy at frequencies below 10 *Hz*. The energy below these frequencies was as high as the noise floor of the reference measurement system. Velocity ratios for horizontal directions show a complex frequency-dependent behaviour on carpeted floors. The error peaks obtained when measuring the Guralp CMG-5TD on the plate in comparison to the results obtained when measuring on the tile could be due to the rocking of the plate.

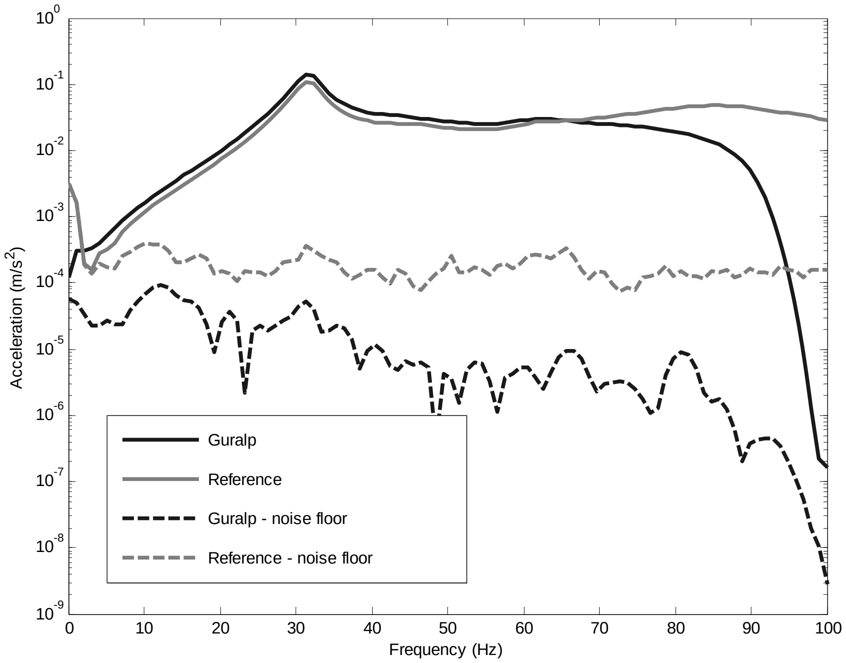



**Figure 17** Frequency response of Guralp CMG-5TD and reference accelerometer (excitation using a sledgehammer).

1. Behaviour of Guralp CMG-5TD on the concrete slab

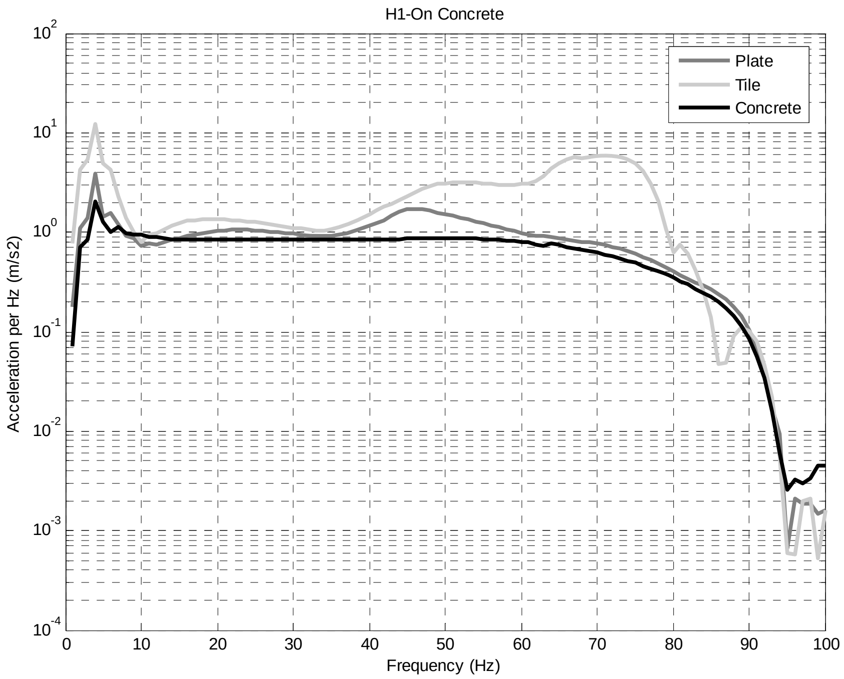



**Figure 18** Velocity ratio between Guralp CMG-5TD and B&K when the Guralp CMG-5TD accelerometer is on concrete, on a ceramic tile and on a metal plate (vertical direction).

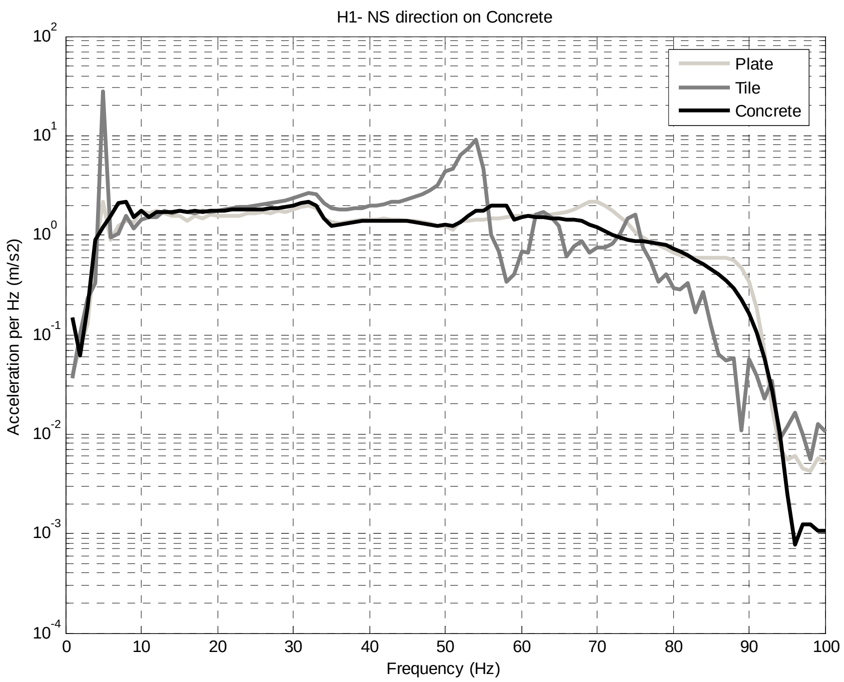



**Figure 19** Velocity ratio between Guralp CMG-5TD and B&K when the Guralp CMG-5TD accelerometer is on concrete, on a ceramic tile and on a metal plate (Horizontal direction).

2. Behaviour of Guralp CMG-5TD on a carpet 1.5 *cm* thick

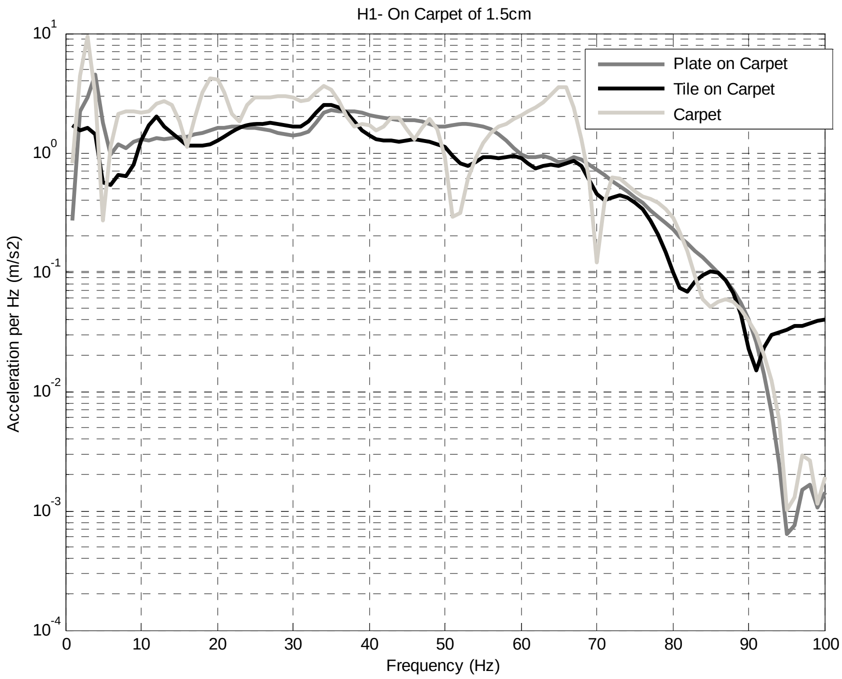



**Figure 20** Velocity ratio between Guralp CMG-5TD and B&K when the Guralp accelerometer is on a carpet of 1.5 *cm*, on a ceramic tile placed on the carpet and on a metal plate placed on the carpet (vertical direction).

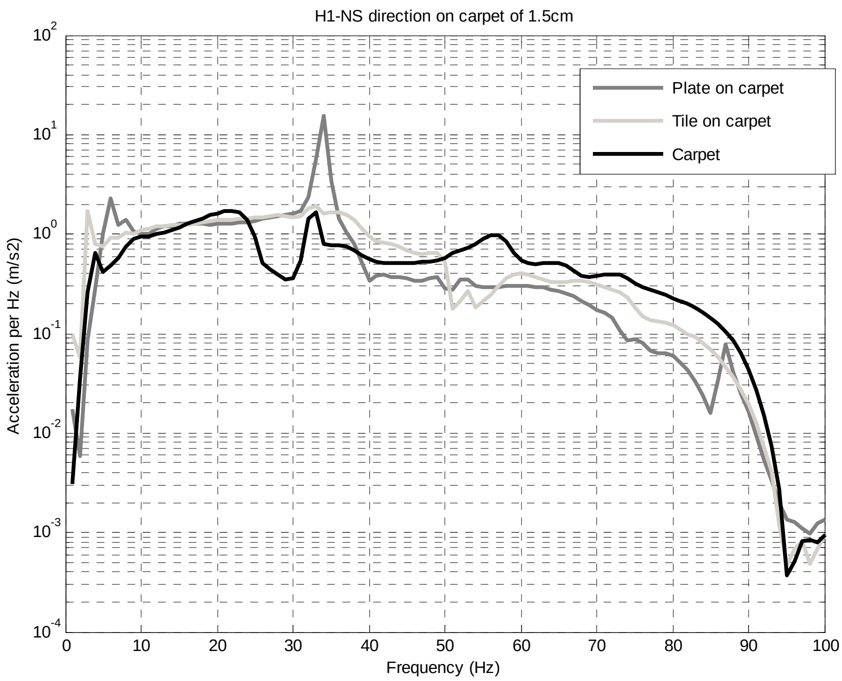



**Figure 21** Velocity ratio between Guralp CMG- 5TD and B&K when the Guralp accelerometer is on a carpet of 1.5 *cm*, on a ceramic tile placed on the carpet and on a metal plate placed on the carpet (Horizontal direction).

3. Behaviour of Guralp CMG-5TD on a carpet 1*cm* thick

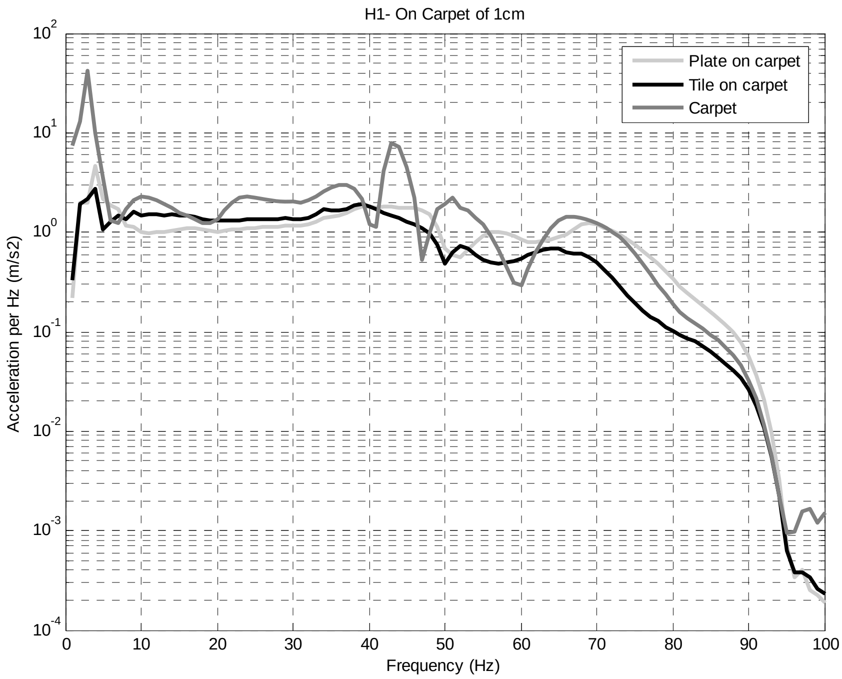



**Figure 22** Velocity ratio between Guralp CMG-5TD and B&K when the Guralp accelerometer is on a carpet of 1 *cm*, on a ceramic tile placed on the carpet and on a metal plate placed on the carpet (vertical direction).

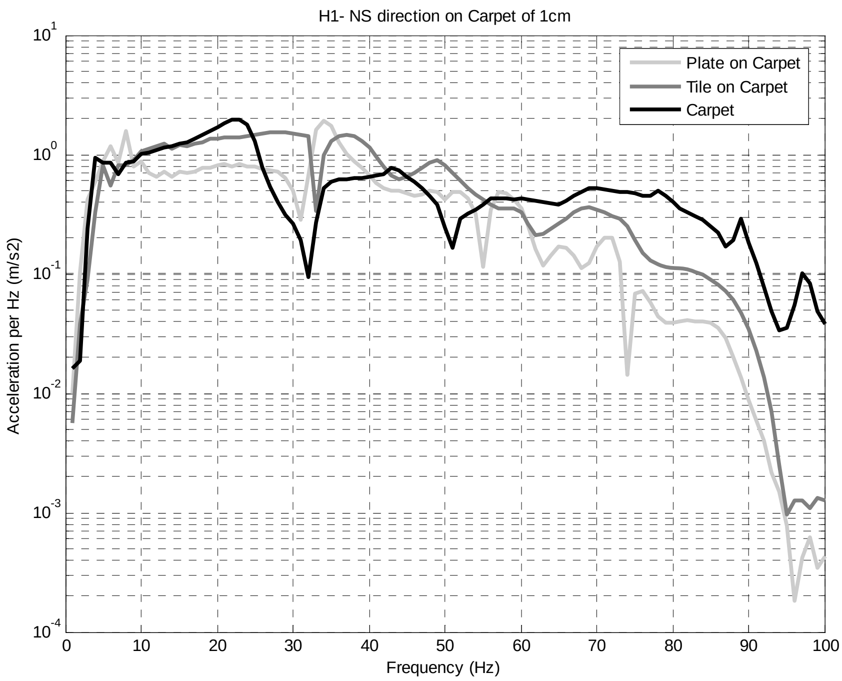



**Figure 23** Velocity ratio between Guralp CMG 5TD and B&K when the Guralp accelerometer is on a carpet of 1 *cm*, on a ceramic tile placed on the carpet and on a metal plate placed on the carpet (horizontal direction).

4. Behaviour of Guralp CMG-5TD on a carpet 0.7 *cm* thick

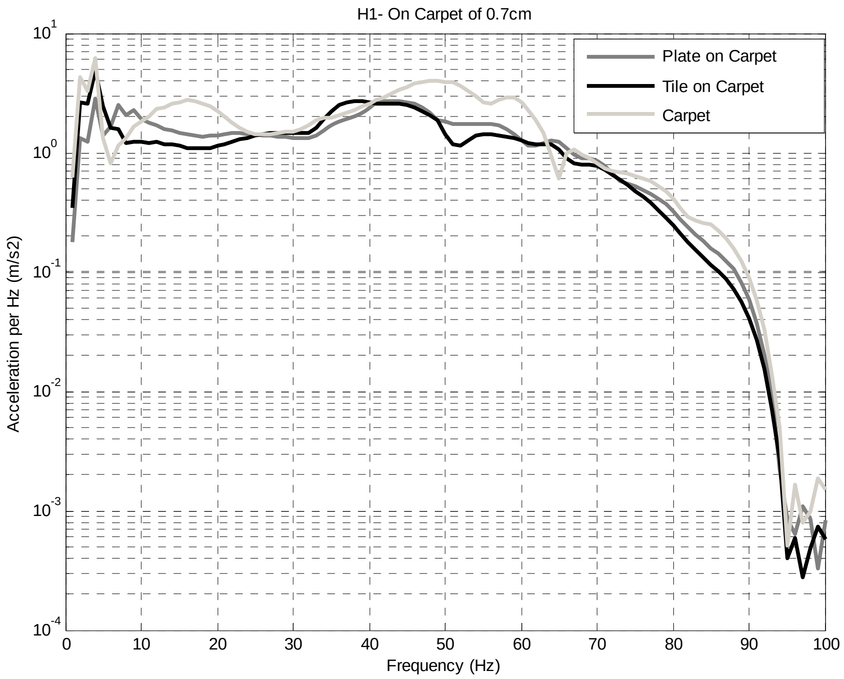



**Figure 24** Velocity ratio between Guralp CMG-5TD and B&K when Guralp accelerometer is on a carpet of 0.7 *cm*, on a ceramic tile placed on the carpet and on a metal plate placed on the carpet (vertical axis).


**Figure 25** Velocity ratio between Guralp CMG-5TD and B&K when the Guralp accelerometer is on a carpet of 0.7 *cm*, on a ceramic tile placed on the carpet and on a metal plate placed on the carpet (horizontal direction).

# APPENDIX 2: INFLUENCE OF THE HUMAN LOAD ON VIBRATION MEASUREMENTS

In order to determine the influence of a standing human body on the vibration measurements (on a structure like a floor in terms of range of frequency and magnitude) an approach similar to the problem of the vibration transmission of machinery was employed. In this way the ratio between the loaded and the unloaded velocity for every point of the structure as a function of the mobilities of the human body and structure can be expressed.

## 1. VIBRATION TRANSMISSION FROM MACHINERY APPROACH

The approach consists in a source that "stands" and transmits vibration to a receiving structure. It is usually necessary to treat both, the source and the receiving structure, as continuous systems (flexible) even for low frequencies. Such a description of linear systems of source and receiver is obtained by means of the mobilities.

The source and receiver structures are commonly coupled to each other at several discrete points. The word ‘point’ is used in a somewhat extended meaning, denoting an area with dimensions smaller than a fraction of a governing vibration wavelength. The physical coupling of the structural subsystems is often constituted by relatively small elastic elements (shocks, isolators, etc.) called transmission elements. If no transmission elements are present, the interface between the source and the receiver is located below the footings.

The described machinery approach (Cremer et al., 2005) was used for modelling the human body standing on a floor scenario. In this case the source (the human body in a standing position) receives vibration from the receiving structure (the floor). In fact, the building is connected to the ground through the foundations and consequently receiving vibrations from the sources belonging to the residential environment.

At first, if the “unloaded” case is considered, a point on the structure **R** (See Figure 26) oscillates with a velocity:

$$\vec{v}_R = \vec{v}_{fs} \qquad \textbf{Equation 2}$$

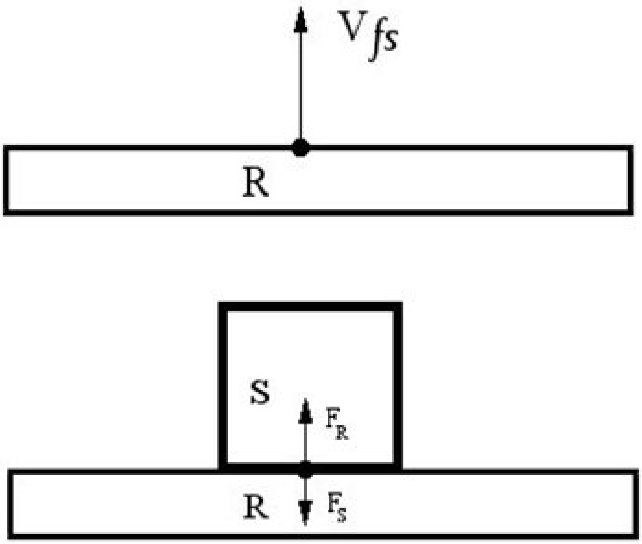



**Figure 26** From top to bottom: Structure R unlodad, Structure R loaded.

If the structure is loaded with a second structure (**S**), the structure **R** gives rise to a reaction force $\vec{F}_R$ at the load of the source $\vec{F}_S$ .

Therefore, the velocity at the contact point of the receiver becomes:

$$\vec{v}_R = \vec{v}_{fs} + Y_R \vec{F}_R$$ **Equation 3**

Whereas the velocity at the contact point of the source is:

$$\vec{v}_S = Y_S \vec{F}_S$$ **Equation 4**

At the interface the conditions for velocity and force must be:

$$\vec{v}_S = \vec{v}_R$$ **Equation 5**

$$\vec{F}_S = -\vec{F}_R$$ **Equation 6**

Substituting Equation 5 and Equation 6 in Equation 3 and Equation 4 it is obtained:

$$\vec{v}_S = Y_S \vec{F}_S$$ **Equation 7**

$$\vec{v}_S = \vec{v}_{fs} - Y_R \vec{F}_S$$ **Equation 8**

From Equation 7 it is worked out $F_S = Y_S^{-1} \vec{v}_s$ and using Equation 8 the following relation only for velocities and mobilities is obtained:

$$\vec{v}_S = \vec{v}_{fs} - Y_R Y_S^{-1} \vec{v}_s$$ **Equation 9**

Rearranging the terms of the above equation, the ratio between the velocity of the loaded and unloaded structure is function of the structure mobilities **R** and **S** are obtained.

$$\frac{\vec{v}_S}{\vec{v}_{fs}} = \frac{1}{1 + Y_R Y_S^{-1}}$$ **Equation 10**

If the structure **S** is considered as a human body **B** in the standing position and our structure **R** is considered to be the floor **F** the relation becomes (Mayr & Gibbs, 2008):

$$\frac{\vec{v}_B}{\vec{v}_{fs}} = \frac{1}{1 + Y_F Y_B^{-1}}$$ **Equation 11**

## 2. MODELLING OF FLOOR MOBILITY

An estimation of the floor mobility where the human body stands is needed. The simplest case is the situation where a person stands on a beam of the floor. In the proximity of a beam the mobility of the floor is similar to the mobility of the beam (Mayr & Nightingale, 2007). Following this approach the vibration of interest on a beam of the floor can be measured. Thus, using this hypothesis a good estimation of the floor mobility using the beam mobility can be derived. For a simply supported beam the force mobility from excited point $x_o$ to an arbitrary point $x$ on beam is given by (Xin, 2003):

$$Y_{vF} = -\frac{j\omega}{2Bk}\left(\frac{\sinh(kx)\sinh(k(l-x_0))}{\sinh(kl)} - \frac{\sin(kx)\sin(k(l-x_0))}{\sin(kl)}\right) \quad 0 \le x \le x_0$$

**Equation 12**

$$Y_{vF} = -\frac{j\omega}{2Bk}\left(\frac{\sinh(kx_0)\sinh(k(l-x_0))}{\sinh(kl)} - \frac{\sin(kx_0)\sin(k(l-x_0))}{\sin(kl)}\right) \quad x_0 \le x \le l$$

**Equation 13**

Where $k = (\omega^2 m' / B)^{1/4}$ is the bending wave number, $m'$ the linear density, B the bending stiffness, $\omega$ the angular frequency and $l$ the length of the beam.

In our case we have the situation where $x = x_0$ because the mobility of the beam at the contact point between the beam and the human body in standing position is needed. Figure 27 shows the trend of a mobility for a wood and concrete beam with a length of 4.55 *m*, width 0.096 *m*, height 0.192 *m* and with $x = x_0$ =2.275 (at the centre of the beam).

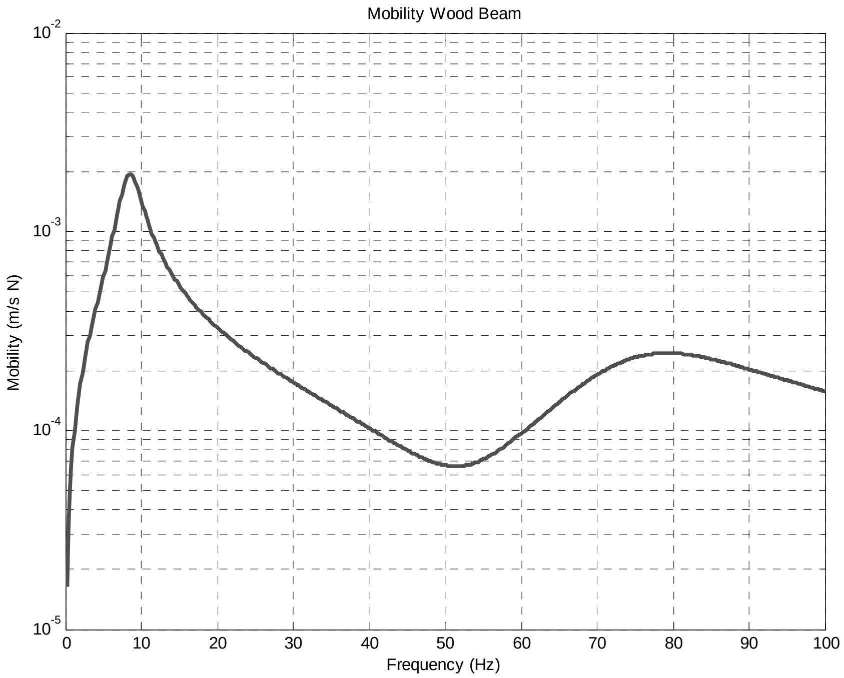



**Figure 27** Mobility wood beam of 4.55 *m* length, width 0.096 *m* width, 0.192 *m* height, and with $x = x_0 = 2.275$

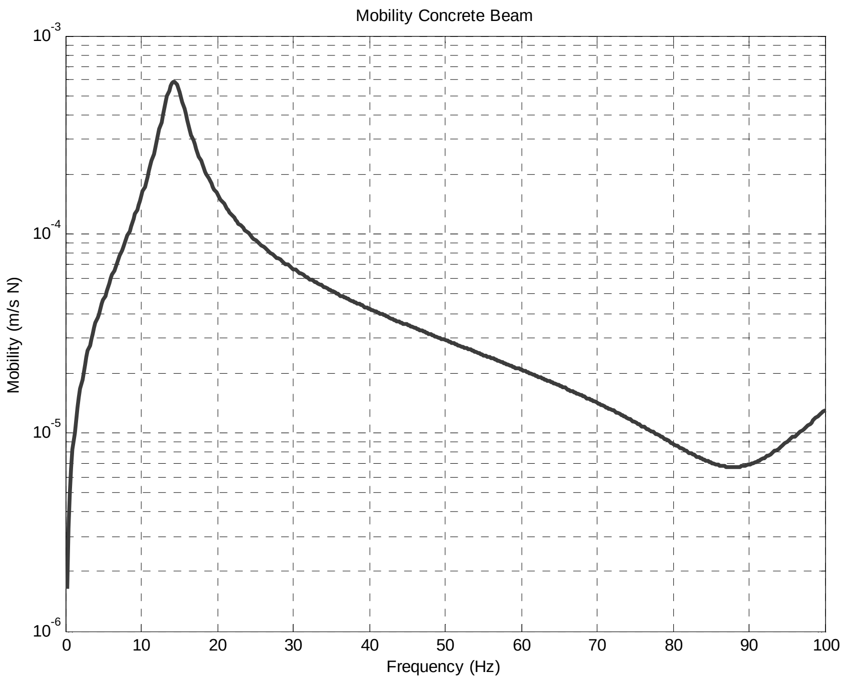



**Figure 28** Mobility concrete beam of 4.55 *m* length, width 0.096 *m* width, 0.192 *m* height, and with $x = x_0 = 2.275$

The damping $\eta$ of the beam is estimated using the empirical relationship in Equation 14 (Craik, 1996). The frequency $f$ is associated with the first resonance of the beam. For a wooden beam the first resonance is around 8 *Hz* and therefore the damping associated is 0.37. On the other hand the damping of a concrete beam is 0.28 because the first resonance is around 14 *Hz*.

$$\eta = \frac{1}{\sqrt{f}} + 0.015$$ **Equation 14**

## 3. MODELLING OF HUMAN BODY MOBILITY

The mobility of the standing human body is derived from the mathematical model of the apparent mass of standing subjects exposed to vertical whole-body vibration made by Matsumoto and Griffin (2003).

$$M_{2a}(i\omega) = \frac{(ic_1\omega + k_1)[m_1(-m_2\omega^2 + ic_2\omega + k_2) + m_2(ic_2\omega + k_2)]}{[-m_1\omega^2 + i(c_1 + c_2)\omega + (k_1 + k_2)](-m_2\omega^2 + ic_2\omega + k_2) - (ic_2\omega + k_s)^2}$$

**Equation 15**

Where $k_1, k_2, c_1, c_2, m_1, m_2$ are parameters of a linear lumped two (degrees of freedom) model.

This model used two mass-spring-damper systems in series. The model parameters were optimised using both the mean apparent mass of 12 male subjects and the apparent masses of individual subjects measured in a previous study (Wai & Griffin, 1998). The mean normalised apparent mass was used in the parameter identification, so the mass parameter has no unit. Correspondingly, the units of the stiffness and damping parameters, based on SI units $[Nm^{-1}]$ and $[Nsm^{-1}]$ respectively, were divided by the unit of mass [*kg*].

| $k_1$ | $k_2$ | $c_1$ | $c_2$ | $m_1$ | $m_2$ |
|---|---|---|---|---|---|
| 4.39 x $10^3$ | 5.53 x $10^2$ | 3.78 x $10^1$ | 1.18 x $10^1$ | 5.74 x $10^{-1}$ | 3.94 x $10^{-1}$ |

Nominal corresponding parameters for a specific static mass of the body can be obtained by multiplying the parameters shown above by the static mass. From the apparent mass of a specific static mass the accelerance is worked out as below:

$$A = \frac{1}{m_{2a}}$$ **Equation 16**

Therefore, the mobility of the human body in the standing position is:

$$Y_b = \frac{1}{j\omega} A$$ **Equation 17**

The apparent mass and the mobility of a human body are represented in Figure 29 and Figure 30 respectively.

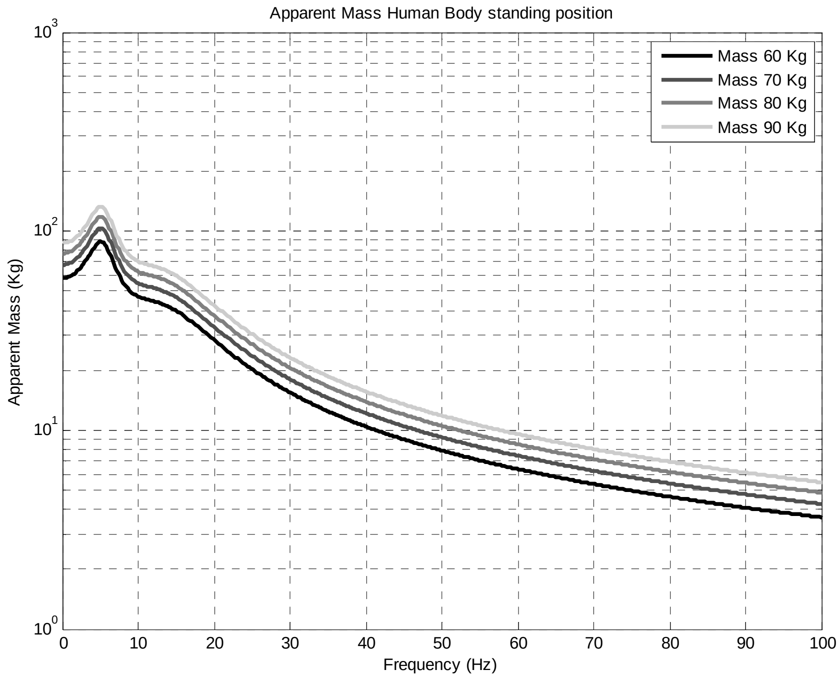



**Figure 29** Apparent mass of human body on a standing position.

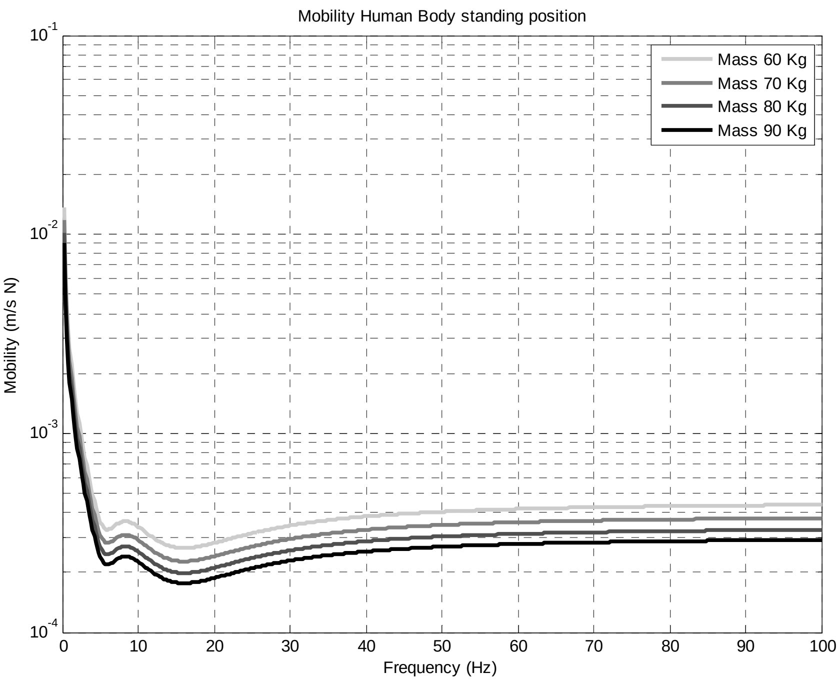



**Figure 30** Mobility of human body on a standing position.

# 3. INFLUENCE OF THE STANDING HUMAN BODY

At this point the influence of the standing human body on a structure, specifically on a floor will be determined.

The influence of the standing human body on a beam using the relation that links the ratio between the velocity of the loaded and unloaded floor with the mobilities of the beam and the human body is worked out using Equation 10 and Equation 11.

Previously, the mobility of the floor with the mobility of the beam were modelled assuming that the vibration is measured on a beam of the floor and also justifying that in the proximity of a beam the mobility of the floor is similar to the mobility of the beam (Equation 12 and Equation 13). The mobility of the human body comes from Equation 17 derived by the apparent mass in Equation 16.

The influence of the human load in the frequency domain for a wooden beam of 4.55 m length, 0.096 *m* width, 0.192 m height and with $x = x_0$ =2.275 and for  is shown in Figure 31. It can be seen that the ratio is almost 1 for frequencies above 50 *Hz* whereas it oscillates between 2 and 10 for frequencies under 50 *Hz*.

From Figure 32 it can be seen that at low frequencies (below 50 Hz) the beam has a higher mobility with respect to the human body in the standing position especially around its first vibration mode.

The mobility of an unloaded beam against the mobility of the loaded beam is expressed as:

$$Y_{lb} = (Y_{beam}^{-1} + Y_{load}^{-1})^{-1} \qquad \textbf{Equation 18}$$

It can be deduced from Figure 33 that a small overestimation of the measured vibration is likely to occur for this scenario.

Figure 34 show the influence of the human load on a concrete beam of  2.5 m length, 0.096 m width, 0.192 m height and with $x = x_0$ =1.25 (centre of beam).

The results presented here were a first step towards understanding the influence of a standing human load on a floor. The resonance of the beam is damping controlled (wooden beam $\eta$ =0.37, concrete beam $\eta$ =0.28) and the overestimation of vibration when measuring on an unloaded beam is small, as the one presented in Figure 33 or Figure 36. However, for an accurate estimation of the effect of the human load, an investigation into the real damping of a wooden beam and concrete beam is needed.

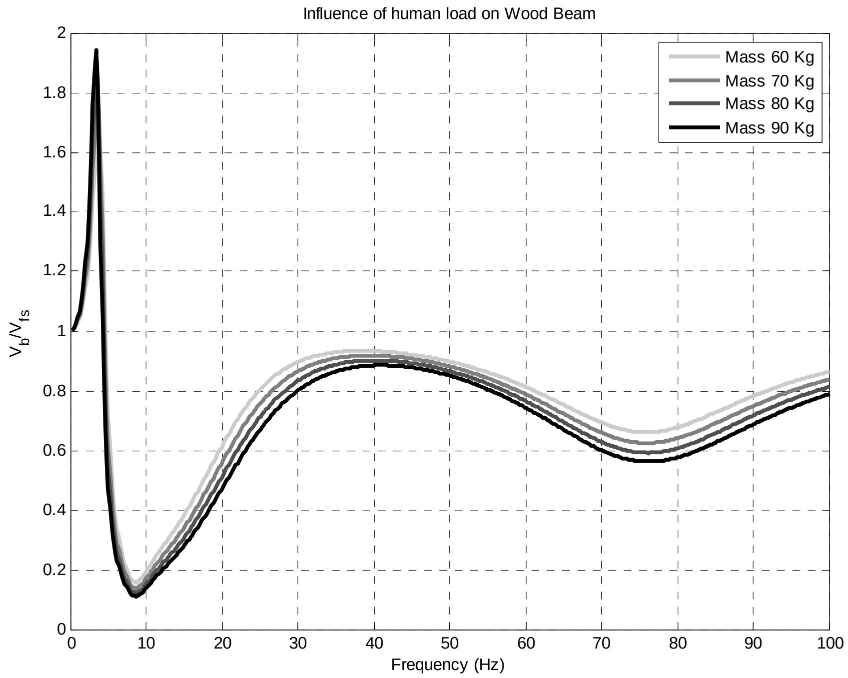



**Figure 31** Influence of human load on wood beam of 4.55 *m* length, width 0.096 *m* width, 0.192 *m* height, and with x = $x_0$=2.275

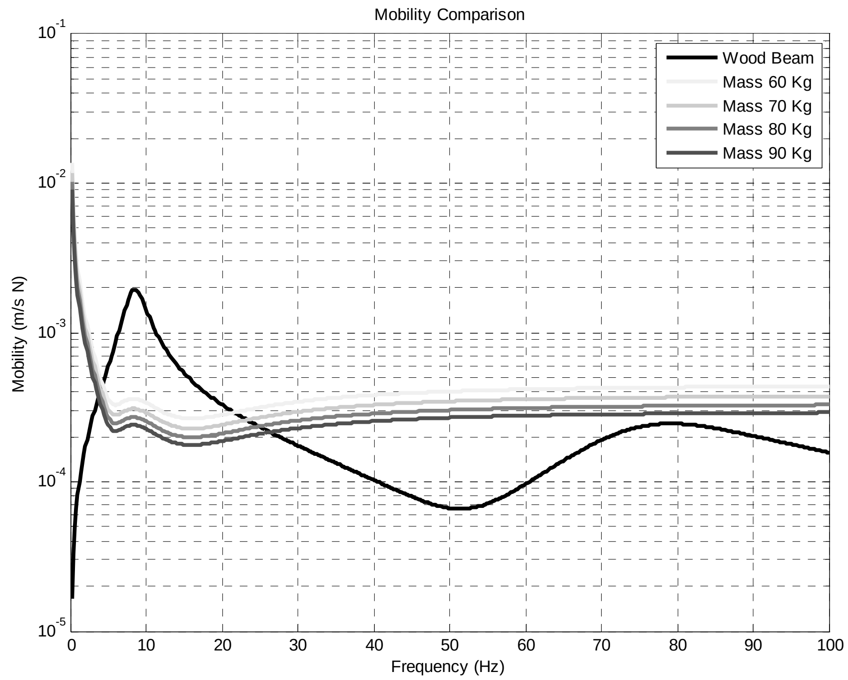



**Figure 32** Mobility comparison

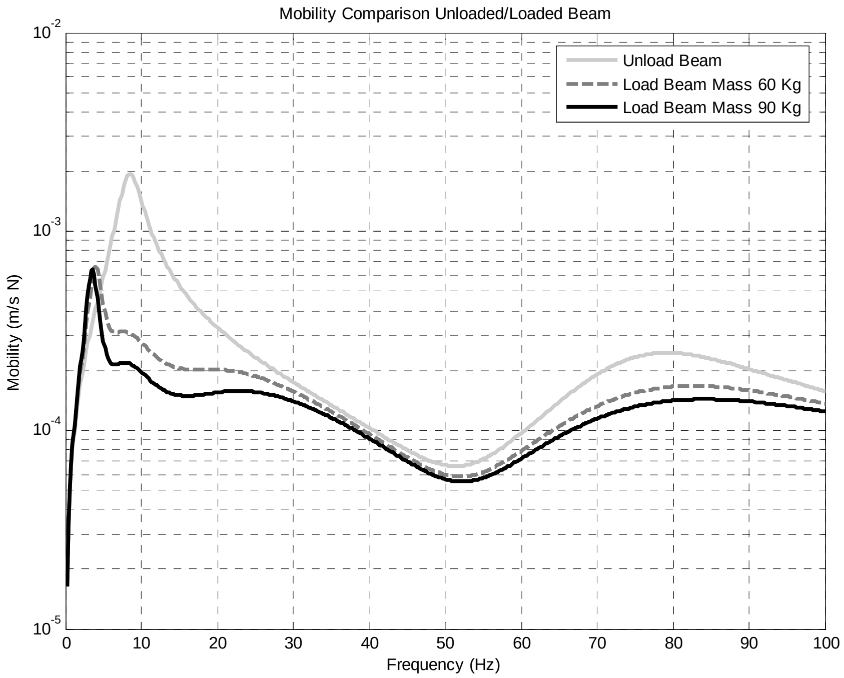



**Figure 33** Mobility comparison unloaded/loaded wooden beam.

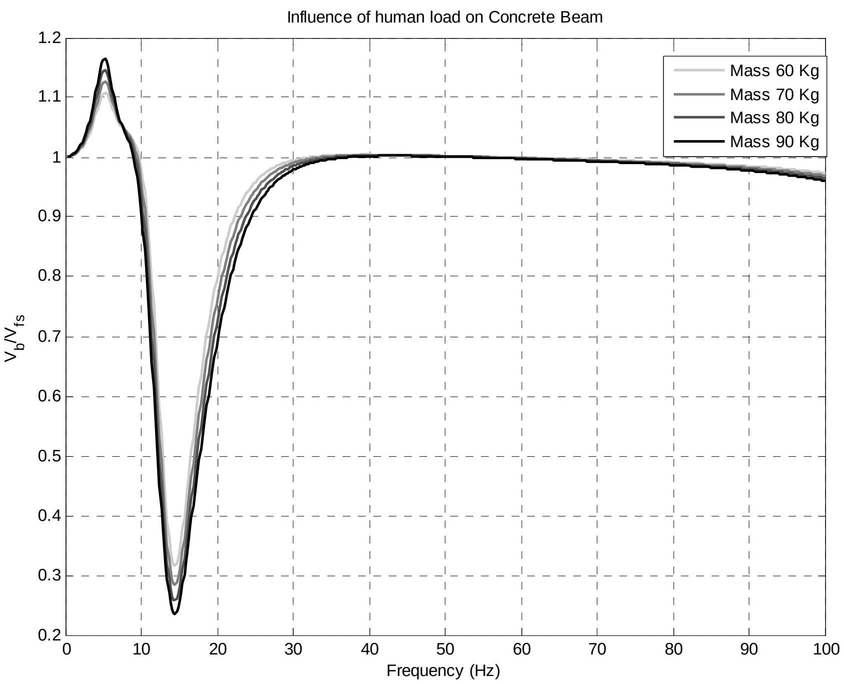



**Figure 34** Influence human load on a concrete beam

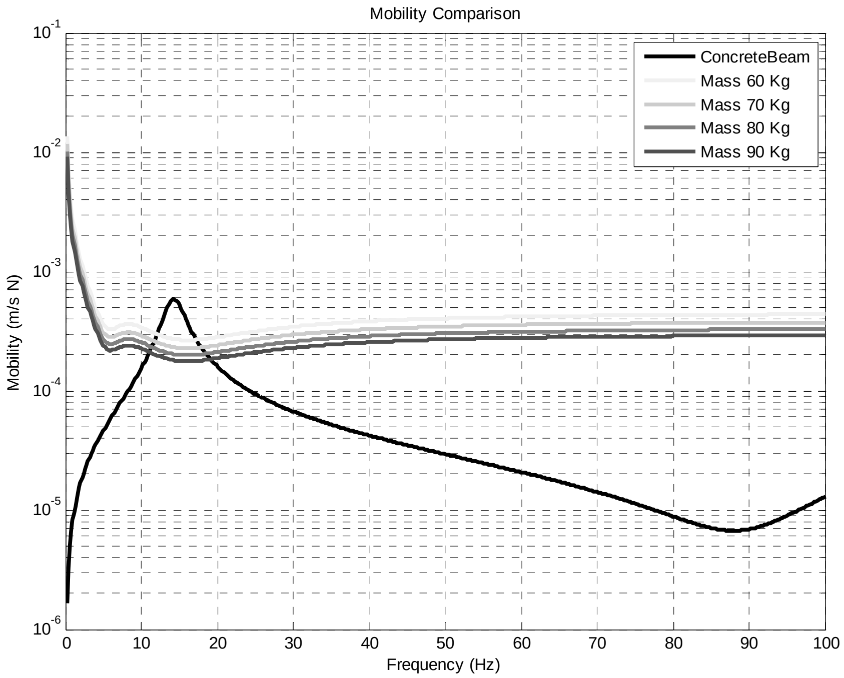



**Figure 35** Mobility comparison

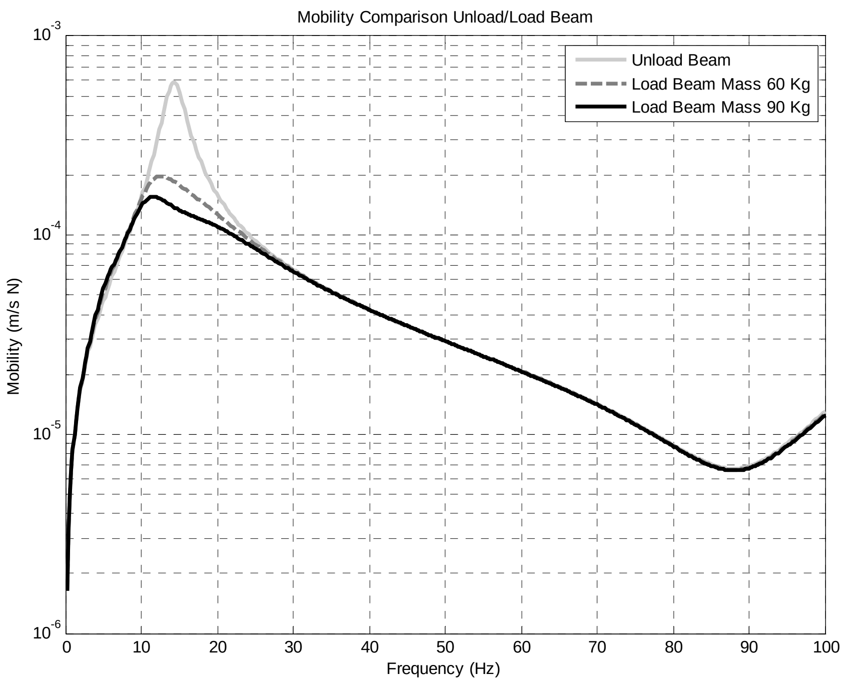



**Figure 36** Mobility comparison uloaded/loaded concrete beam

# APPENDIX 3: SAMPLE CALIBRATION CERTIFICATE

GURALP SYSTEMS

Guralp Systems Limited, 3 Midas House, Calleva Park,
Aldermaston, Reading, RG7 8EA, UK.
Telephone: +44 118 9819056 Fax: +44 118 9819943
sales@guralp.com

***CMG-5T/TD/U Instrument Quality Certificate***

This certificate identifies the tests and inspection carried out.

**Sensor Serial Number.** T5064

| | Pass |
|---|---|
| Sensor Noise Coherence. | |
| Frequency response. Document attached. | ✓ |
| Calibration. Document attached. | ✓ |
| **Cable Lengths & Ancillaries as per customer order?** | |

Final Quality Approval.

On behalf of Guralp Systems. Date 8-9-09

GURALP SYSTEMS LIMITED, REGISTERED OFFICE, 3 MIDAS HOUSE, CALLEVA PARK, ALDERMASTON, READING, RG7 8EA
REGISTERED IN ENGLAND No. 2199239. VAT REGISTRATION No. 491 4657 20.

5T Sensor Quality Certificate TRV-T50-0001-B

# CMG-5TD CALIBRATION
## (ACCELERATION OUTPUTS)

**WORKS ORDER:** 5062 **SERIAL NUMBER:** T5O64 /A1626

| | | | |
|---|---|---|---|
| SYSTEM ID: | 5062 | | |
| UNIT ID: | 5O64 | BOOTLOADER | MK3BOOT103.IMG |
| OUTPUT DATA FORMAT: | GCF | DSP SOFTWARE: | DSPSI1060.BIN |
| BAUD RATE: | 38400 | SYSTEM: | DMNET103b78.IMG |

ACCELERATION CHANNELS

| Steam ID | Component | Digitiser Input | Acceleration | Digital Output |
|---|---|---|---|---|
| 5O64Z2 | Vertical | 3.209 µV/Count | 2.038 $V/m/s^2$ | 635178.46 $Counts/m/s^2$ |
| 5O64N2 | North/South | 3.187 µV/Count | 2.036 $V/m/s^2$ | 638772.08 $Counts/m/s^2$ |
| 5O64E2 | East/West | 3.202 µV/Count | 2.040 $V/m/s^2$ | 637200.48 $Counts/m/s^2$ |

CAL SIGNAL MONITOR

5O64X2 3.204 µV/Count

GPS RECEIVER

PWM 8000 Counts @ 23°C

POWER CONSUMPTION

| | |
|---|---|
| Digitiser | 80mA @ 12v |
| GPS | 28mA @ 12v |
| Sensor | 51mA @ 12v |

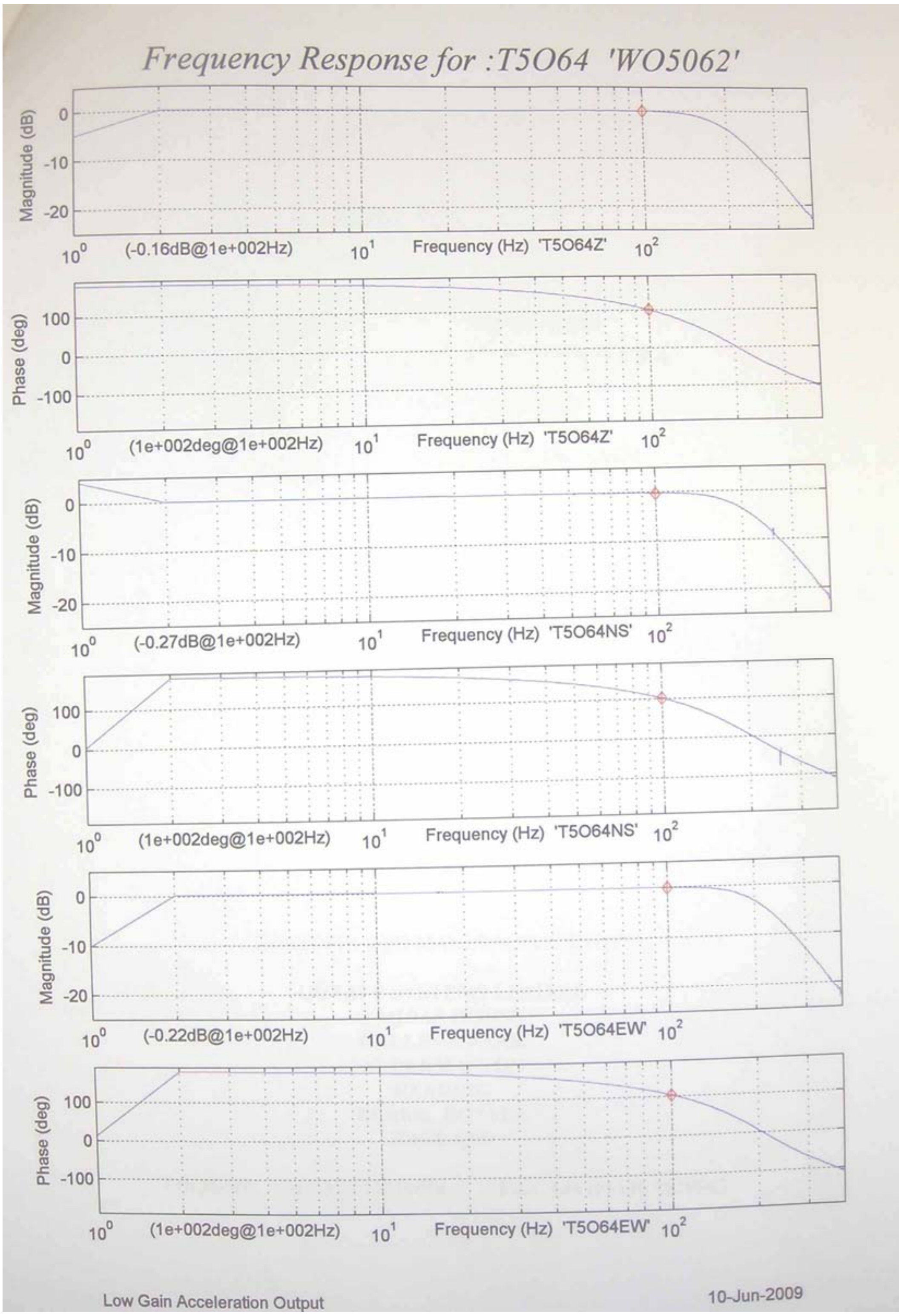
## CMG-5T ABSOLUTE CALIBRATION
(ACCELERATION OUTPUTS)

| | | | |
|---|---|---|---|
| WORKS ORDER: | 5062 | DATE: | 08/06/2009 |
| SERIAL NUMBER: | T5O64 | TESTED BY: | MM |
| | | OUTPUT at 1g | 10 volts |

| | Acceleration Response $V/m/s^2$ |
|---|---|
| VERTICAL | 2 x 1.019 |
| NORTH/SOUTH | 2 x 1.018 |
| EAST/WEST | 2 x 1.020 |

| | |
|---|---|
| Vertical component equivalent acceleration from calibration signal of: | 1 Volt = 0.491 $m/s^2$ |
| North/South component equivalent acceleration from calibration signal of: | 1 Volt = 0.491 $m/s^2$ |
| East/West component equivalent acceleration from calibration signal of: | 1 Volt = 0.490 $m/s^2$ |
| Calibration enable signal polarity: | Active Low |
| Typical Current Consumption: | N/A |
| This sensor operates from: | 10 to 36 Volts |

NOTE: A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.


Frequency Response for :T5O64 'WO5062'
Magnitude (dB)
0
-10
-20
10^0
(-0.16dB@1e+002Hz)
10^1
Frequency (Hz) 'T5O64Z'
10^2
Phase (deg)
100
0
-100
10^0
(1e+002deg@1e+002Hz)
10^1
Frequency (Hz) 'T5O64Z'
10^2
Magnitude (dB)
0
-10
-20
10^0
(-0.27dB@1e+002Hz)
10^1
Frequency (Hz) 'T5O64NS'
10^2
Phase (deg)
100
0
-100
10^0
(1e+002deg@1e+002Hz)
10^1
Frequency (Hz) 'T5O64NS'
10^2
Magnitude (dB)
0
-10
-20
10^0
(-0.22dB@1e+002Hz)
10^1
Frequency (Hz) 'T5O64EW'
10^2
Phase (deg)
100
0
-100
10^0
(1e+002deg@1e+002Hz)
10^1
Frequency (Hz) 'T5O64EW'
10^2
Low Gain Acceleration Output
10-Jun-2009